BOEING

Volume V

Phase I, Final Briefing
Executive Summary
D180-25037-5

NASA CR-160374

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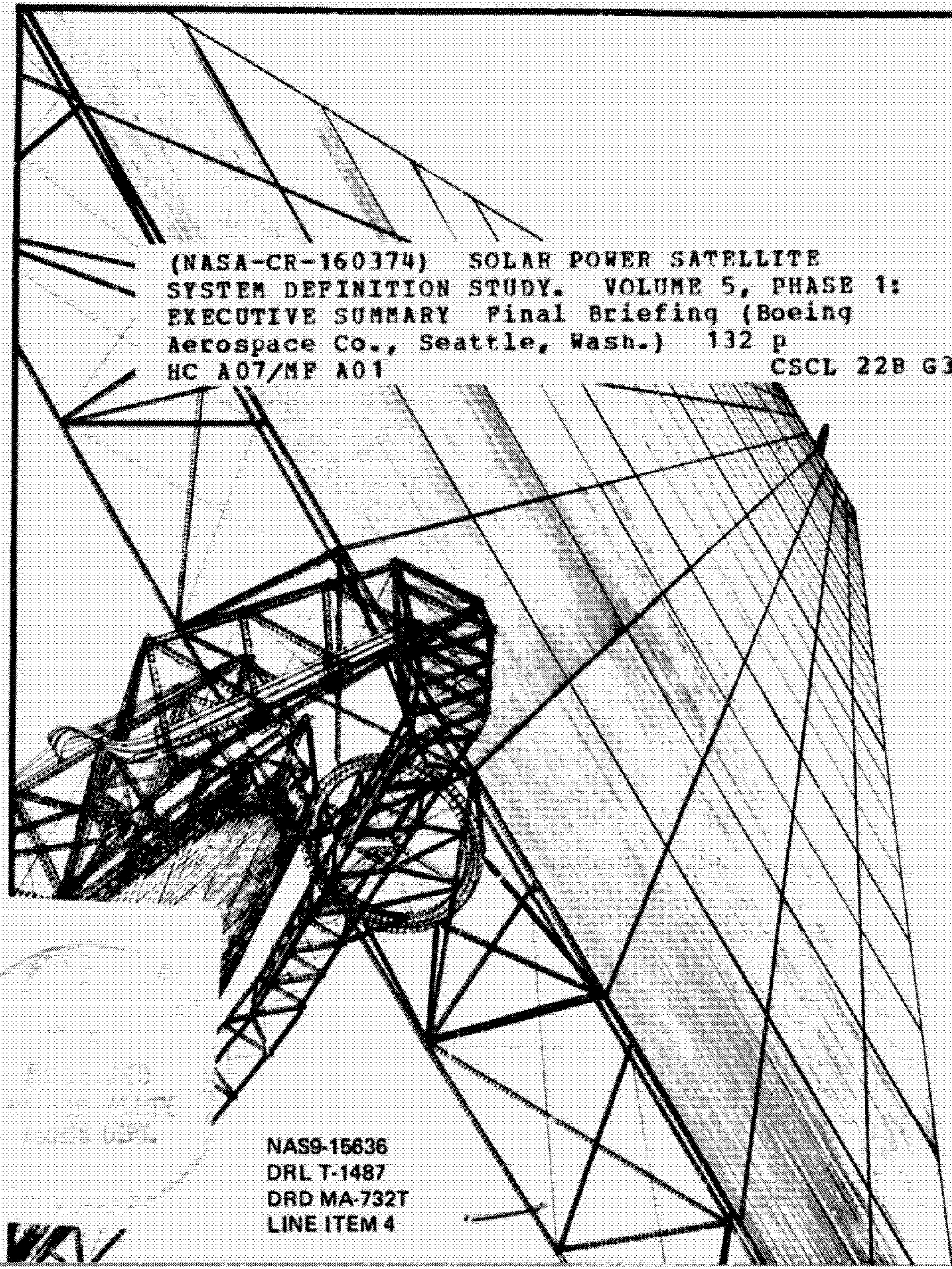

Solar Power Satellite System Definition Study

BOEING

GENERAL ELECTRIC

GRUMMAN

Arthur D Little Inc

TRW

NAS9-15636
DRL T-1487
DRD MA-732T
LINE ITEM 4

Solar Power Satellite
System Definition Study
Conducted for the NASA Johnson Space Center
Under Contract NAS9-15636

Volume V
PHASE I, FINAL BRIEFING
Executive Summary
D180-25037-5

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FOREWORD

The SPS System Definition Study was initiated in June of 1978. Phase I of this effort was completed in December of 1978 and is herewith reported. This study is a follow-on effort to an earlier study of the same title completed in March of 1978. These studies are a part of an overall SPS evaluation effort sponsored by the U. S. Department of Energy (DOE) and the National Aeronautics and Space Administration.

This study is being managed by the Lyndon B. Johnson Space Center. The Contracting Officer is Thomas Mancuso. The Contracting Officer's representative and Study Technical Manager is Harold Benson. The study is being conducted by The Boeing Company with Arthur D. Little, General Electric, Grumman, and TRW as subcontractors. The study manager for Boeing is Gordon Woodcock. Subcontractor managers are Dr. Philip Chapman (ADL), Roman Andryczyk (GE), Ronald McCaffrey (Grumman), and Ronal Crisman (TRW).

This report includes a total of seven volumes:

I - Executive Summary
II - Phase I Systems Analyses and Tradeoffs
III - Reference System Description
IV - Silicon Solar Cell Annealing Tests
V - Phase I Final Briefing Executive Summary
VI - Phase I Final Briefing: Space Construction and Transportation
VII - Phase I Final Briefing: SPS and Rectenna Systems Analyses

In addition, General Electric will supply a supplemental briefing on rectenna construction.

Agenda

THURSDAY, DEC 14TH

0900	EXECUTIVE SUMMARY	G. WOODCOCK
	TOPICAL REPORT I: SPACE OPERATIONS	
1045	CONSTRUCTION LOCATION ANALYSIS	E. DAVIS
1200	(LUNCH)	
1300	SATELLITE CONSTRUCTION ANALYSIS	K. MILLER, R. McCAFFREY
1430	ALUMINUM SATELLITE STRUCTURE	R. McCAFFREY
	TOPICAL REPORT II: GROUND OPERATIONS	
1500	INDUSTRIAL INFRASTRUCTURE	P. CHAPMAN
1530	RECTENNA SITING	D. GREGORY

FRIDAY, DEC 15TH

	TOPICAL REPORT III: SATELLITE & RECETNNA SYSTEMS	
0900	SOLAR ARRAYS AND ANNEALING	O. DENMAN
0930	ONBOARD POWER HANDLING	O. DENMAN
0945	ONBOARD DATA & COMMUNICATIONS	R. CRISMAN
1015	POWER TRANSMISSION SYSTEM	E. NALOS
1100	POWER RECEPTION SYSTEM	R. ANDRYCZYK
1200	(LUNCH)	
	TOPICAL REPORT IV: DEVELOPMENT PLANNING	
1300	TECHNOLOGY ADVANCEMENT	G. WOODCOCK
1330	FLIGHT PROJECTS	D. GREGORY

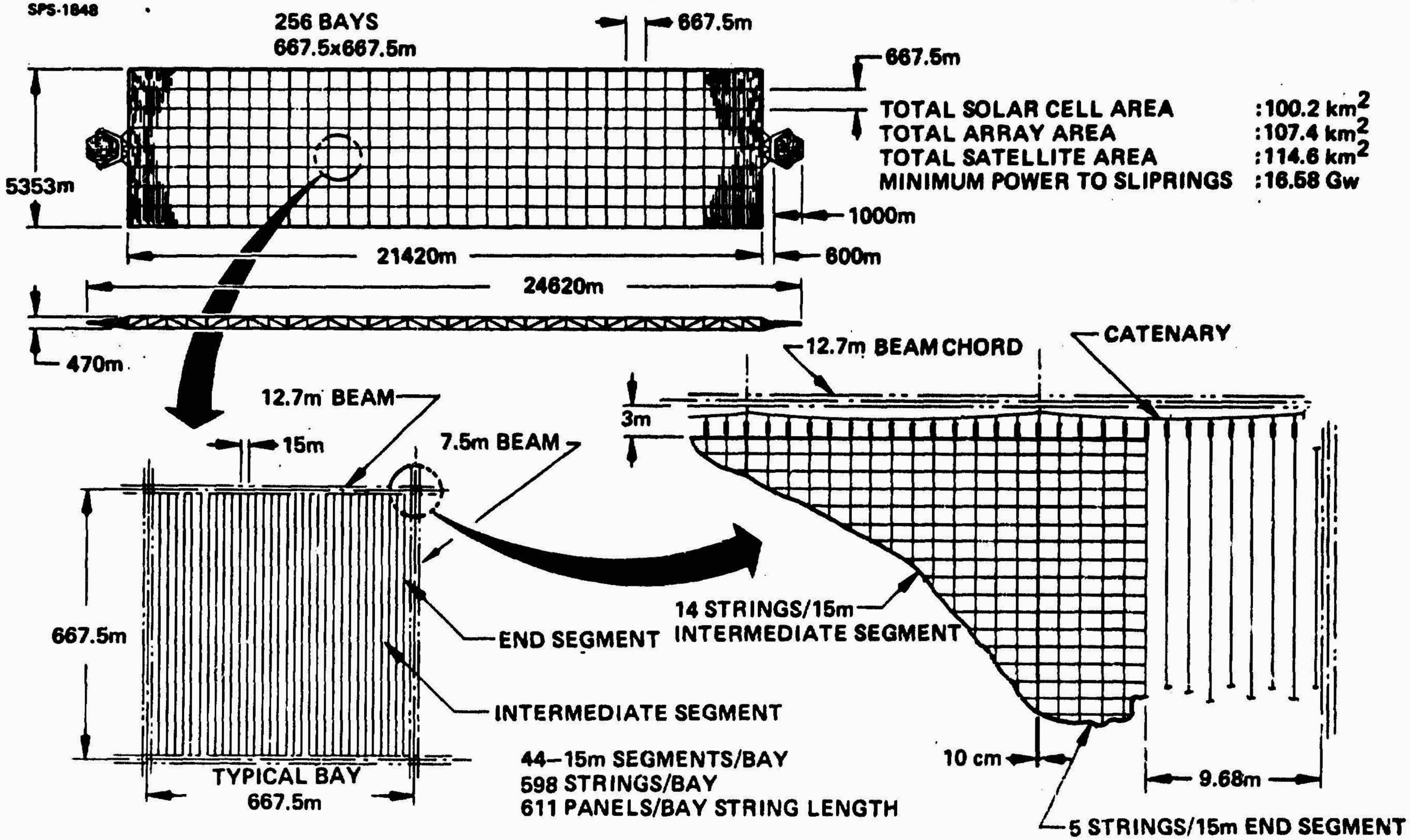
REFERENCE PHOTOVOLTAIC SYSTEM DESCRIPTION

Shown here is the reference SPS system size and configuration from the earlier study, the point of departure for the current study. Details are shown of a typical bay and the array support within the bay.

The array segment width is 14.9 meters. This provided better packaging for transport but made it necessary to provide 15-meter catenary attachment points on the structural beams. A 10-cm spacing was provided between array segments for clearance during array deployment.

Reference Photovoltaic System Description

SPS-1848



STUDY CONTRACT TEAM ORGANIZATION

The Study Contract Team includes Boeing as prime contractor and General Electric, Grumman, Arthur D. Little, and TRW as subcontractors. Principal task areas for the subcontractors are shown and the study team leaders for each contractor are indicated.

Study Contract Team Organization (Phase I Tasks Shown)

BOEING — G. R. WOODCOCK

- **GENERAL ELECTRIC** — R. ANDRYCZYK
  - PHASE CONTROL INSTALLATION
  - RECTENNA CONSTRUCTION & MAINTENANCE
  - RECTENNA-GRID POWER PROCESSING
- **GRUMMAN** — R. McCAFFREY
  - SPACE CONSTRUCTION OPTIONS
  - ALUMINUM STRUCTURE
- **A. D. LITTLE** — P. CHAPMAN
  - EFFECTS OF POWER BEAM ON SPACECRAFT
  - INDUSTRIAL COMPLEX
- **TRW** — R. CRISMAN
  - MISSION CONTROL CONCEPTS
  - SPS AVIONICS & DATA SYSTEM

EXECUTIVE SUMMARY

The executive summary is subdivided into three major parts: (1) highlights of trades and analyses, (2) the study baseline update and recommendation and (3) a discussion of development planning.

- **HIGHLIGHTS OF TRADES AND ANALYSES**

  ANNEALING & BLANKET DESIGN
  ALUMINUM STRUCTURE
  SOLID STATE POWER AMPLIFIER
  FAILURE ANALYSES
  SMALLER SPS'S
  IEOTV AND CONSTRUCTION LOCATION
  CONSTRUCTION BASE OPTIONS
  LAUNCH SITES AND TRAJECTORIES
  MISSION CONTROL
  INDUSTRIAL INFRASTRUCTURE

- **STUDY BASELINE UPDATE AND RECOMMENDATIONS**

- **DEVELOPMENT PLANNING**

THIRTY YEAR FLUENCE COMPARISON

As a part of the independent electric OTV analysis, a careful comparative study of the available data for silicon and gallium arsenide solar cells was conducted. This analysis revealed a significant difference in the environment model used for the Boeing and Rockwell solar blanket degradation analyses. The difference represents approximately one order of magnitude in equivalent electron fluence.

30 Year Fluence Comparison

ITEM	BOEING	ROCKWELL
CELL THICKNESS (mils)	2.0	0.2
FRONT SHIELD (COVER)	BOROSILICATE GLASS	Al_2O_3 (SAPPHIRE)
THICKNESS (mils)	3.0	0.8
MASS/AREA (g/m^2)	167.6	79.6
BACK SHIELD (SUBSTRATE)	BOROSILICATE GLASS	FEP/KAPTON
THICKNESS (mils)	2.0	1.6
MASS/AREA/(g/m^2)	111.8	72.0
30 YEAR FLUENCE (1-MeV ELECTRON EQUIV. /cm^2)	2×10^{16}	[1] 4.9×10^{15}

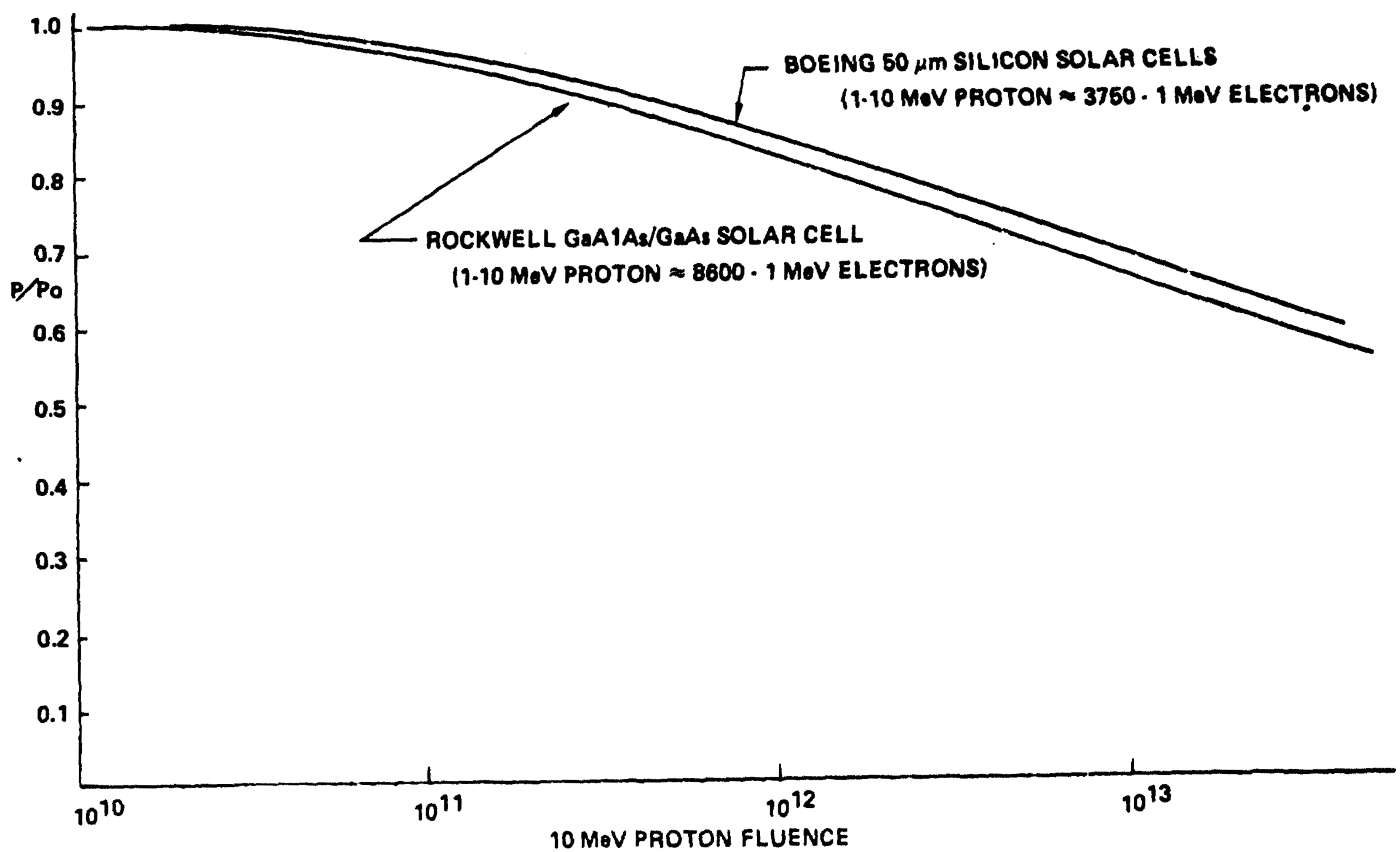
[1] BOEING MODEL WOULD PREDICT APPROX. 6×10^{16} 1-MeV ELECTRON EQUIV./cm^2

DEGRADATION COMPARISON FOR PROTON IRRADIATION

Boeing test data on silicon solar cells are compared here with the Rockwell projections for the gallium arsenide solar cell. It is clear that there is no significant difference in these results. Test data on gallium arsenide cells might, of course, change the results significantly. Note the difference in proton electron equivalences between silicon and gallium arsenide. This difference arises because of the difference in mass of the atoms of the two solar cell constituents. Our analysis would predict no significant difference in degradation between the two systems for the same fluence. Since the gallium arsenide solar blanket design has significantly less shielding, we would predict more degradation in the equivalent environment compared to the Boeing silicon blanket design.

Recent results reported by Hughes show the radiation degradation of gallium arsenide to be a strong function of junction depth. Shallow-junction cells show less degradation. The possibility that gallium arsenide cells may anneal at relatively low temperatures needs to be further explored by testing.

Degradation Comparison For Proton Irradiation

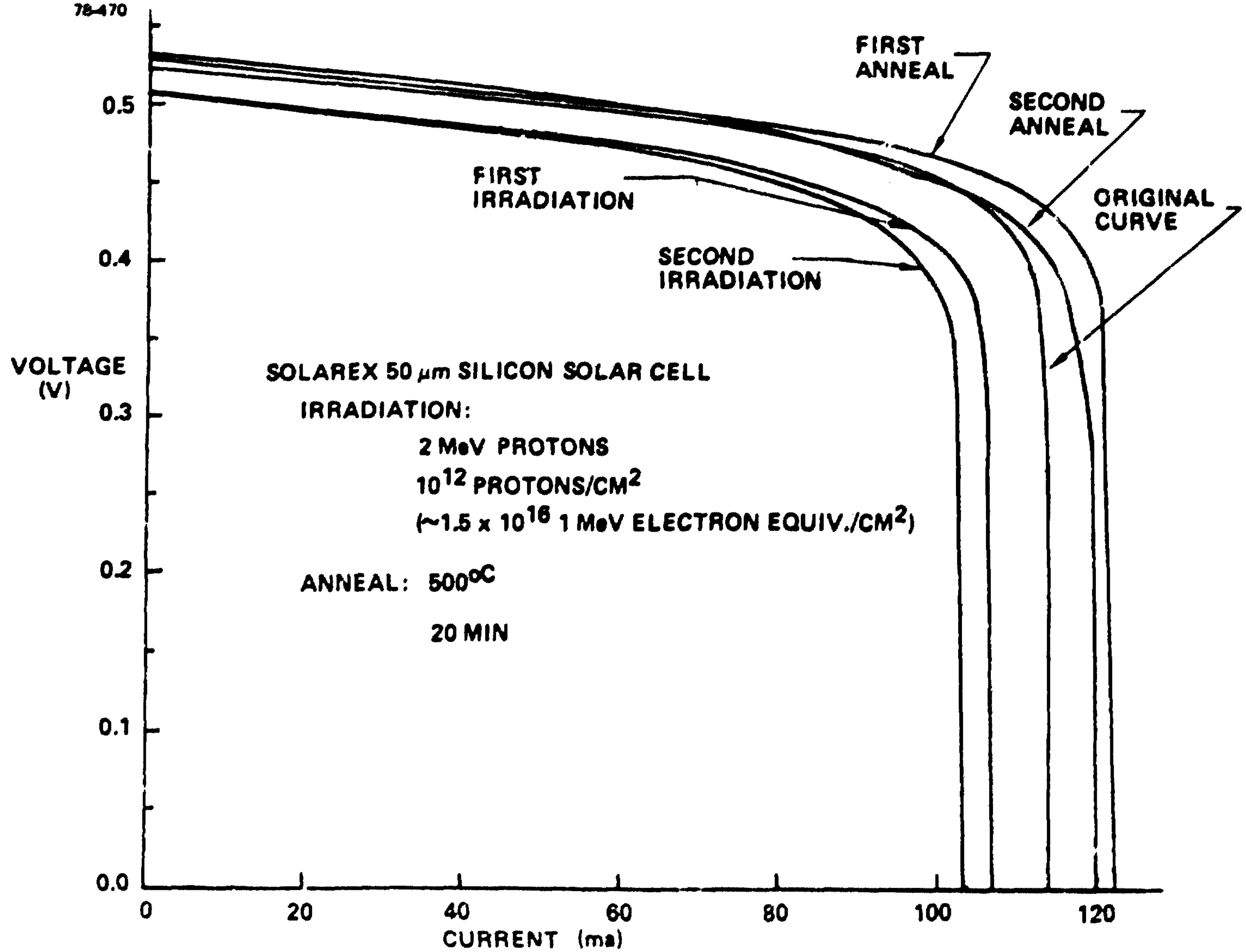


THERMAL ANNEALING OF PROTON DAMAGE IN SILICON BOEING TEST DATA

Illustrated here are the results of oven annealing tests of bare 50 micron silicon solar cells. Several cells were tested with two irradiations and two anneals. There were significant differences in recovery from one cell to the next. Some of these data scatter were attributed to differences in solar cell response characteristic measuring equipment. All cells tested showed recovery on both anneals.

BOEING SPS

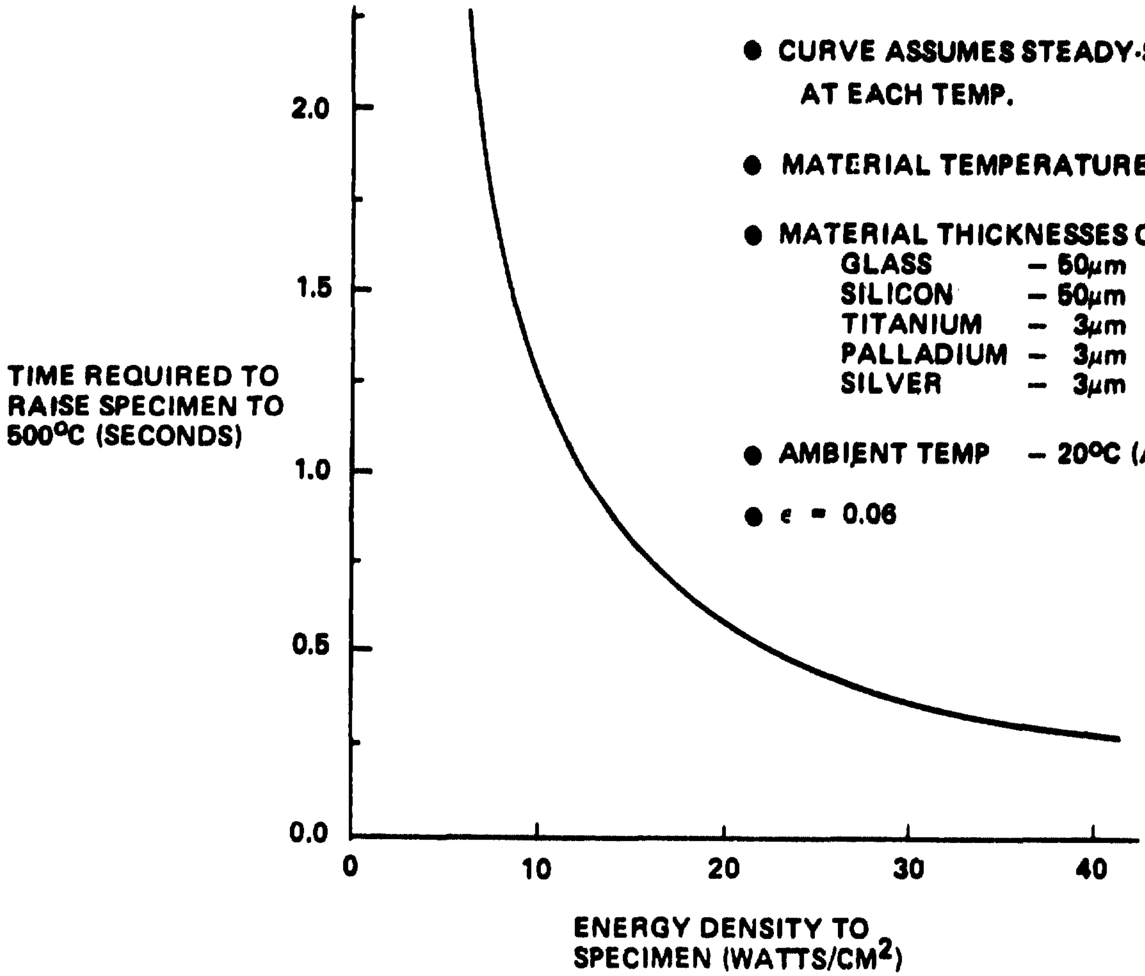
Thermal Annealing of Proton Damage In Silicon: Boeing Test Data



TIME TO TEMPERATURE FOR VARIOUS ANNEALING ENERGY DENSITIES

Initial tests under ECP 001 for laser annealing of thin solar cells with glass covers were directed to measuring thermal response solar cells to laser energy density. The results are shown here. These energy density requirements are less than earlier estimates by about a factor of 5 and have been reflected in reductions in numbers of lasers and power requirements for the reference laser annealing system.

Time-to-Temperature for Various Annealing Energy Densities



- CURVE ASSUMES STEADY-STATE HEAT LOSSES AT EACH TEMP.
- MATERIAL TEMPERATURE GRADIENTS NOT INCLUDED
- MATERIAL THICKNESSES OF SPECIMEN
  - GLASS – 50μm
  - SILICON – 50μm
  - TITANIUM – 3μm
  - PALLADIUM – 3μm
  - SILVER – 3μm
- AMBIENT TEMP – 20°C (AIR)
- ϵ = 0.06

ALUMINUM SOLAR ARRAY STRUCTURE - CONCLUSIONS

One of the baseline evaluation tasks was directed to the use of an aluminum solar array support structure. Grumman performed this task under subcontract. Their conclusions are summarized here.

ALUMINUM SOLAR ARRAY STRUCTURE – CONCLUSIONS

- ROLL FORMED CLOSED SECTION ALUMINUM STRUCTURES CAN BE AUTOMATICALLY FABRICATED IN ORBIT
- DESIGN LOAD REQMTS FOR LEO CONSTRUCTED SPS MODULE ARE SATISFIED – ALUMINUM 23% (2.82×10^5 Kg) HEAVIER THAN COMPOSITE BUT MAY BE LOWER IN COST
- 10 GW SPS NATURAL FREQUENCY WITH ALUMINUM (AR = 4) IS 65 TIMES ORBITAL FREQUENCY – INSTEAD OF 100 TIMES
- ESTIMATED NATURAL FREQUENCY IS ADEQUATE FOR SATELLITE CONTROL SYSTEM STABILITY, FURTHER ANALYSIS REQD TO VERIFY.
- BASED ON INITIAL STUDIES, THERMAL STRESSES ARE WITHIN CAPABILITY OF ALUMINUM DESIGN
- SATELLITE DEFLECTIONS ARE WITHIN ACCEPTABLE LIMITS ($\sim 2°$)

GRUMMAN

SOLID STATE POWER AMPLIFIER

Principal findings and principal issues identified are summarized on the facing page. The solid state power amplifier configuration for a microwave power transmission transmitter seems well suited to low power SPS's. We found the potential for accomplishing definition of a suitable solid state system to be considerably more encouraging than we had expected. Certain key issues remain.

Primary is the need to find a way to eliminate or minimize power processing.

Secondly, experimental verification of acceptable efficiencies for integrated assemblies of amplifier devices, coupling circuits, and RF radiators is needed.

Finally, there is the issue of device cost. Gallium arsenide FET's today cost on the order of $100 per watt. This is obviously prohibitive. A production rate curve extrapolation to quantities appropriate to SPS leads to cost predictions in the acceptable range. These, however, will require further confirmation through experience in larger scale production.

Solid State Power Amplifier

FINDINGS

- IDENTIFIED A PRACTICAL ELEMENT/SUBARRAY DESIGN APPROACH
- SOLID STATE TRANSMITTER IS A MASS/AREA SYSTEM RATHER THAN A MASS/POWER SYSTEM
- GaAs FET'S HAVE ADEQUATE PERFORMANCE–80% EFFICIENCY IS A REASONABLE EXPECTATION
- EFFICIENCY AND THERMAL CAPABILITY YIELD A MAXIMUM TRANSMITTER RATING OF ROUGHLY 2.5 GW GROUND OUTPUT AT 1.4 km DIA.
- EXPECT SIGNIFICANT RELIABILITY ADVANTAGE

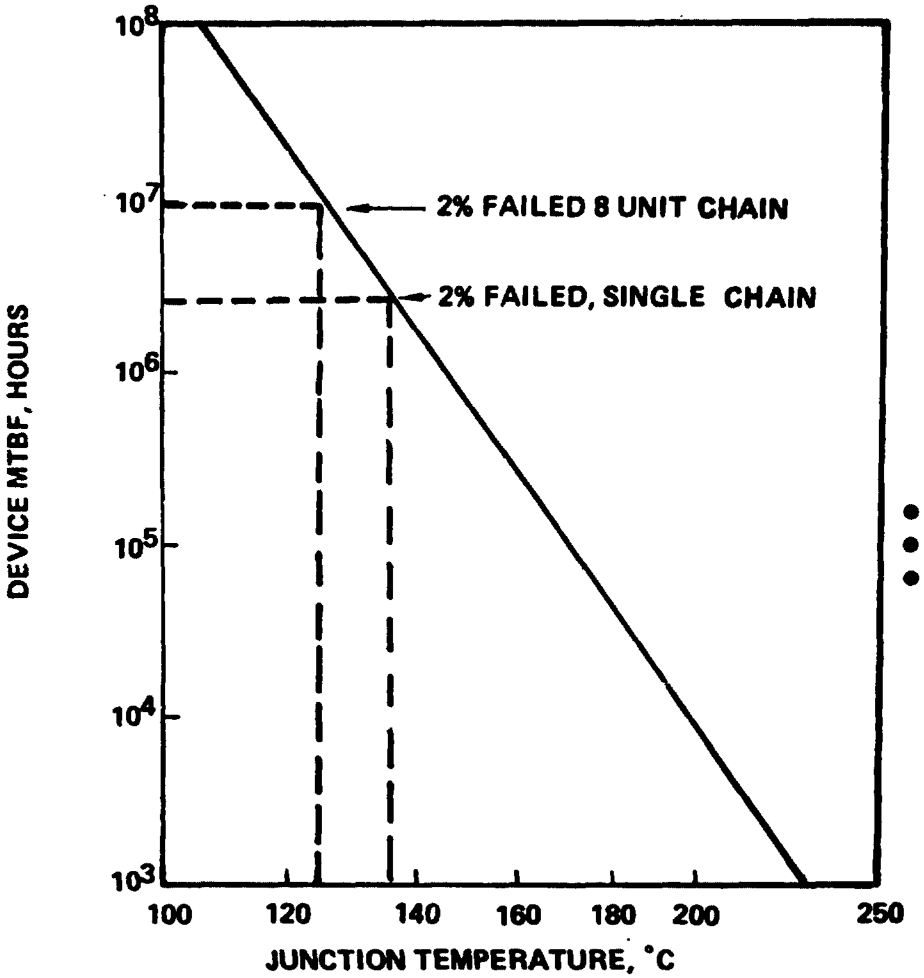
ISSUES

- ELIMINATION OF POWER PROCESSING
- EXPERIMENTAL MEASUREMENT OF INTEGRATED DEVICE/CIRCUIT/ RADIATOR PERFORMANCE: EFFICIENCY, GAIN, NOISE, HARMONICS
- DEVICE COST (NOW ≈ $100/WATT IN LOTS OF 100)

SOLID STATE DEVICE LIFETIMES

The failure statistics indicated in the attached chart show that at a channel temperature of 135°C, 98% of the devices will still be operating after 30 years. This suggests that a no-maintenance mode of operation may be feasible. Even if a single FET failure in a power module consisting of 8 output FET's (say 4 watts each) constituted a total loss of the entire module (no graceful degradation), the operation of such modules @ 125°C would result in 2% loss after 30 years, compatible with SPS failure rate budget.

Solid State Device Lifetime



- GaAs FET
- 30 YEAR MAINTENANCE
- LOG NORMAL FAILURE DISTRIBUTION
  $\sigma = 1$

1978 RELIAB. PHYSICS SYMP.

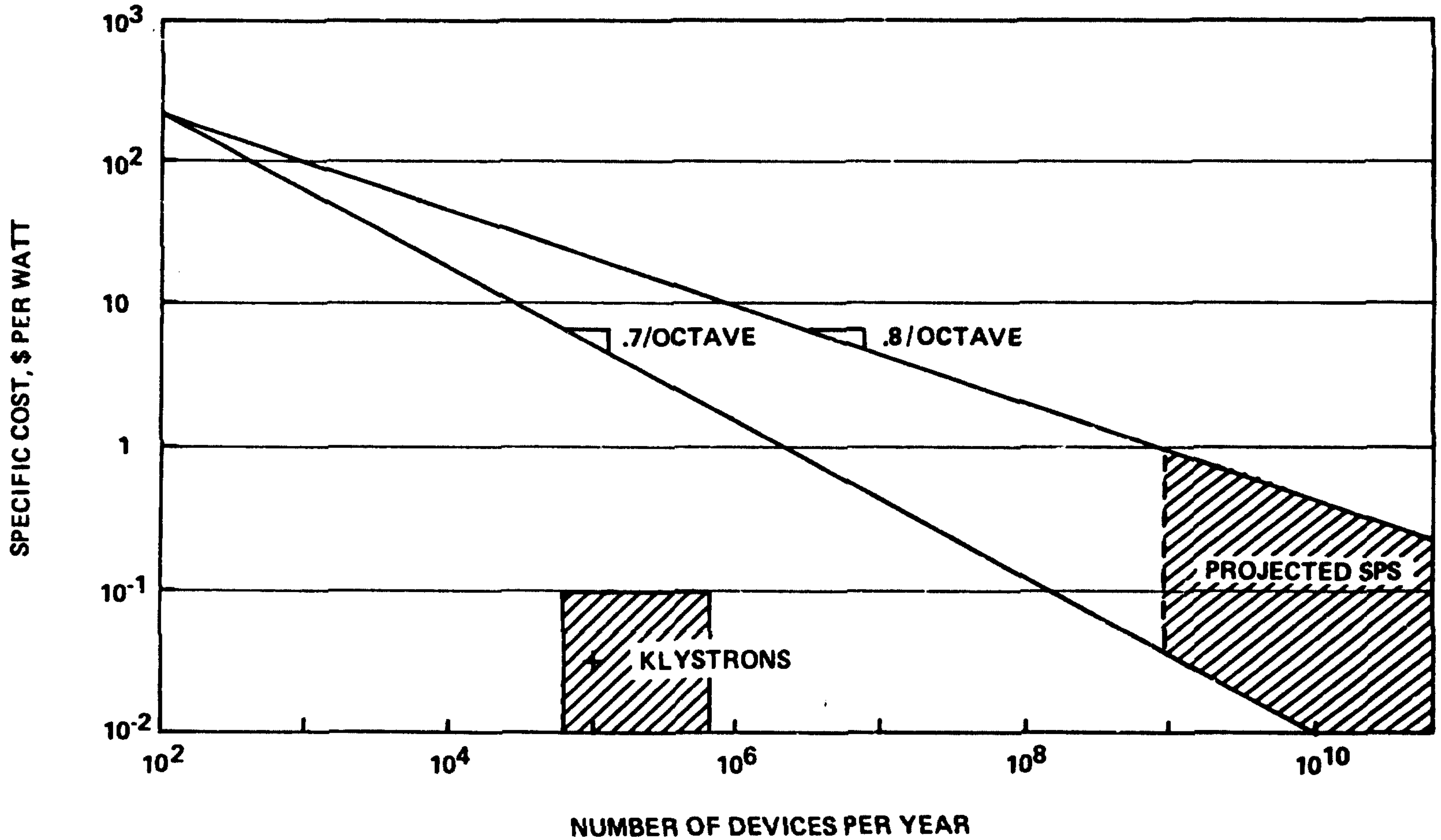
SOLID STATE DEVICE MATURE INDUSTRY COSTING

With a 70% production rate improvement curve (i.e. units produced at the rate of 2n per year cost 70% as much as units produced at the rate of n per year), cost per unit power for GaAs FETS is about the same as the projected cost per unit power for klystrons.

Solid State Device Mature Industry Costing

BOEING

SPS-2326

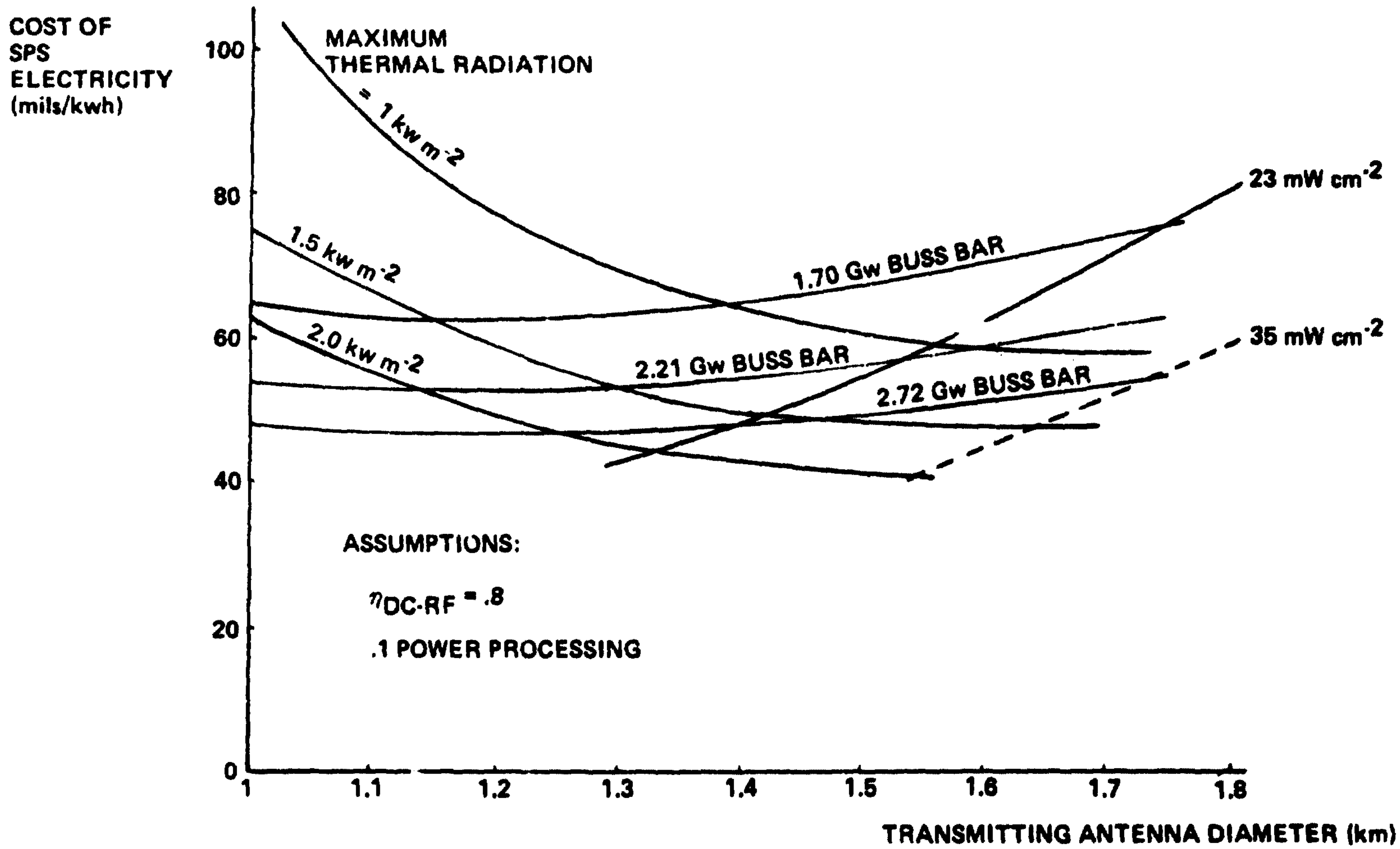


REPRESENTATIVE SOLID STATE SPS COSTS AND SIZING

The solid state transmitter is limited by maximum allowable device temperature to a thermal dissipation of roughly 1.5 kilowatts per square meter. At a conversion efficiency of 80% with a 10 dB Gaussian taper the thermal constraints and ionosphere power density constraints follow characteristic curves as illustrated on this map of SPS power cost indicators versus transmitter diameter and power level. As can be seen, the solid state system is constrained to a total power level of approximately 2½ gigawatts with a transmitter aperture of 1.4 kilometers. Thus, this system is well-suited to the smaller size lower power SPS application and in fact may be limited to such lower power transmitter links.

Representative Solid State SPS Costs and Sizing

SPS-2346



SOLID STATE POWER SUPPLY OPTIONS

Solid state devices suitable for microwave power amplification operates at voltages on the order of 25 volts. Distribution voltages suitable for SPS application range from 20,000 to 40,000 volts. If it were necessary to process all this power down to a voltage of 25 volts, the cost and efficiency of power processing combined with the I^2R losses and conductor mass for such operations might be prohibitive. Therefore, an approach to elimination of power processing is highly desirable. Two approaches have been identified that may prove workable. One is being explored by Rockwell based on earlier suggestions by Aerospace Corporation. This is the idea of distributing the microwave power conversion over the solar array and using a microwave waveguide system for power distribution. In this way, the need for electrical power distribution is eliminated and the solar array can supply power to local microwave generators at low voltage. This option raises serious concerns regarding the degree to which phase control precision can be maintained. The second approach is to employ a series-parallel connection of the microwave power amplifiers (as regards DC power supply) similar to that used for solar cells in generation of the DC power. Aggregate sets of microwave power generators can then be supplied at comparatively high distribution voltages. This option raises concerns regarding stability, matching, and balance of the power supply and control network.

The minimum risk option is use of dc/dc converters but this will result in significantly greater SPS mass and cost.

AC power distribution may provide a means of minimizing distribution losses and reducing solar array voltage. Mass and cost penalties will be similar to those for full dc/dc processing.

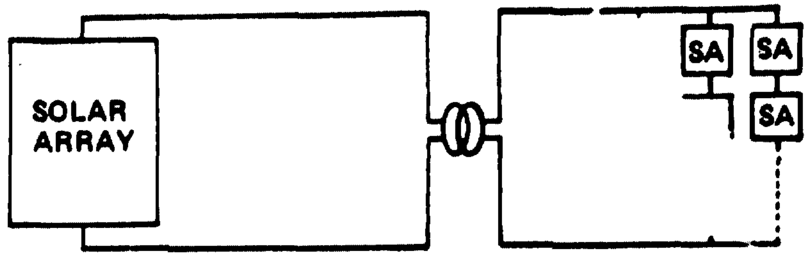
Solid State Power Supply Options

SPS-2542

- DIRECT HIGH VOLTAGE DC

  REQUIRES SUBARRAYS IN SERIES
  CONNECTION TOPOLOGY A PROBLEM

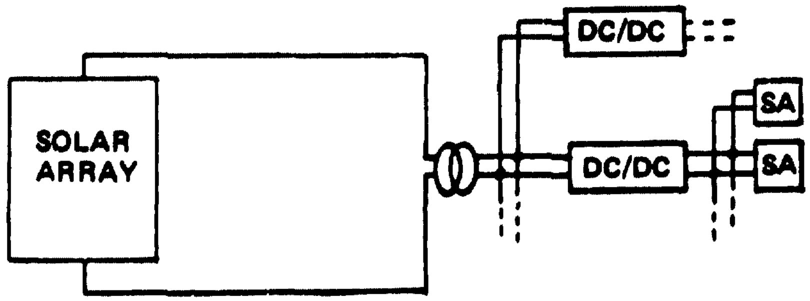
  HIGH E-FIELDS NEAR ADJACENT SUBARRAYS
  MAY CAUSE ARCS, WILL SUSTAIN THEM



- DC-DC CONVERSION ON MPTS

  PERFORMANCE PENALTIES
  DC-DC CONVERTERS ≈ 1kg/kw
  POWER LOSSES IN CONVERTERS

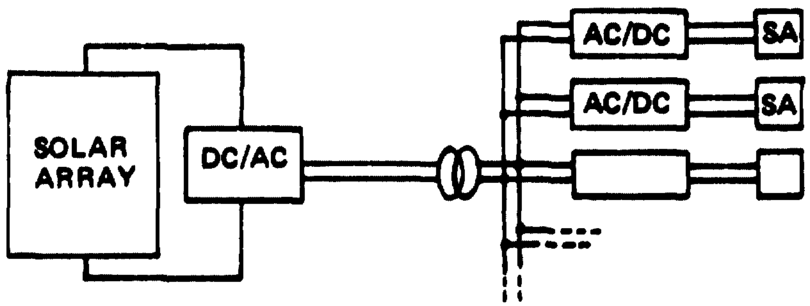
  SERIES/PARALLEL CONNECTIONS WITHIN
  SUBARRAYS STILL REQUIRED



- AC POWER DISTRIBUTION

  CONVERT
  DC/AC ON SOLAR ARRAY
  AC/DC AT SUBARRAY

  REQUIRES S/P TO SOME EXTENT ON SUBARRAY



SPS SATELLITE FAILURE SUMMARY 10 GIGAWATT SPS

Results of the updated failure analysis are recorded here. The numbers of failures per year for these systems represents the maintenance work load for satellite maintenance.

SPS Satellite Failure Summary—10 GW SPS

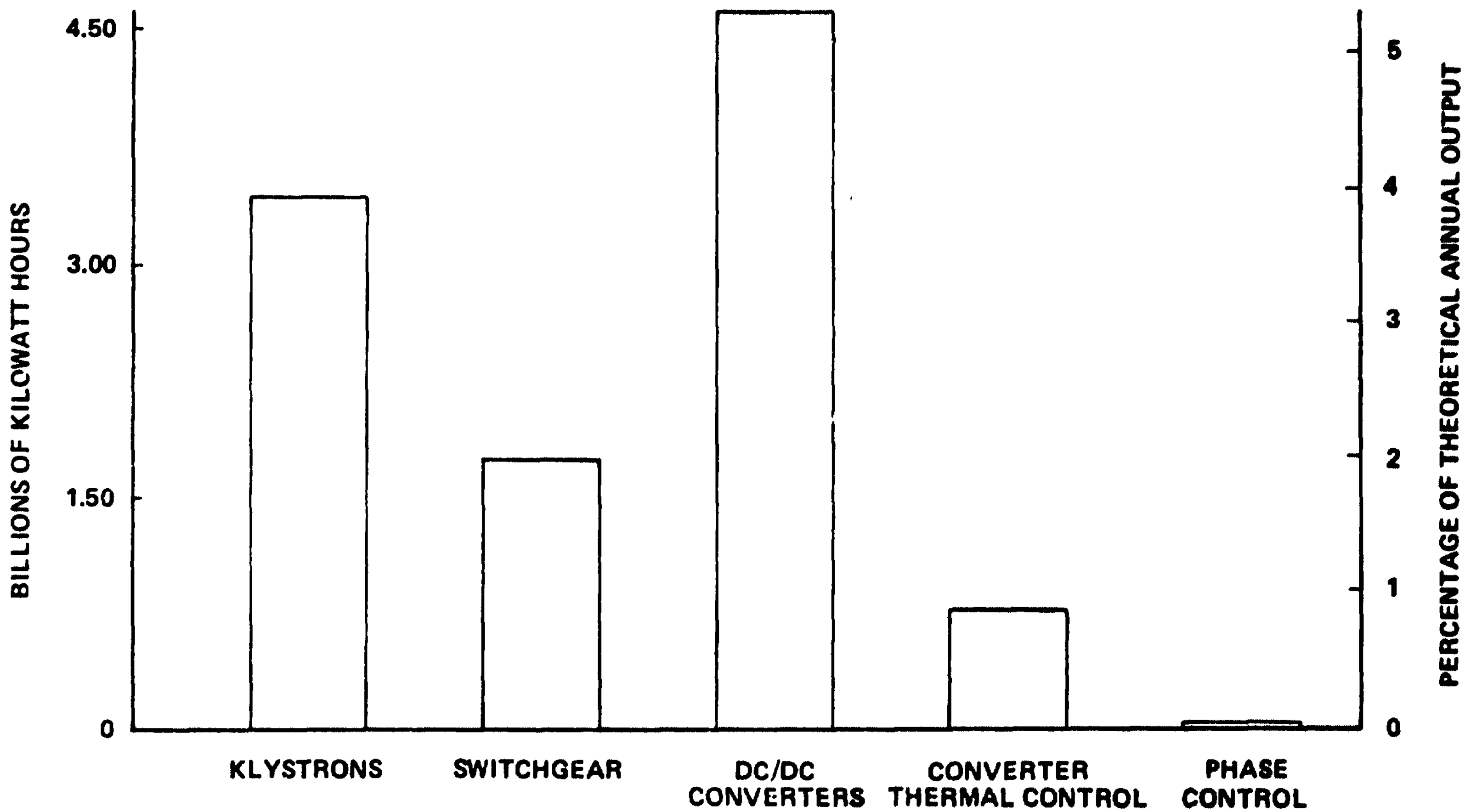
SPS-2475

WBS	NOMENCLATURE	QUANTITY/SPS	FAILURES/YR.
1.1	ENERGY CONVERSION		
1.1.1.1.4	BLANKET TENSIONING DEVICES	337,920	325
1.1.1.3.2	BLANKET MECHANICAL ATTACHMENT	337,920	658
1.1.1.4.5	CELL STRING BLOCKING DIODES	19,072	7
1.1.2	POWER TRANSMISSION		
1.1.2.2.1	RF/DC CONVERTER MODULE	203,104	7,934
1.1.2.3.2	SWITCHGEAR	912	9
1.1.2.3.3	DC/DC CONVERTER	456	24
1.1.2.3.4	DISCONNECT SWITCHES	912	3
1.1.2.4.2	DC/DC CONVERTER THERMAL CONTROL	456	4
1.1.2.5	PHASE CONTROL	203,568	
1.1.2.5.1	RECEIVERS	203,568	4
1.1.2.5.2	DIPLEXERS	203,568	2
1.1.2.5.3	PHASE TRANSMITTERS	220,408	29
1.1.2.5.4	PHASE RECEIVERS	220,408	4
1.1.2.5.5	CONJUGATORS	203,568	33
1.1.2.5.6	CABLING	218,888	26

ANNUAL POWER LOSS DUE TO FAILURES

The annual power loss due to these failures is a function of the number of failures and the power loss per failure. As indicated, the principal power loss problem is the DC-to-DC converters followed by klystrons and switchgear. Investigations have indicated that partial redundancy can be built into the DC-to-DC converters with small mass penalty to reduce this problem.

Annual Power Loss Due To Failures



AVAILABILITY VS. PROBABILITY OF OVERALL SPS POWER TRANSMISSION SYSTEM FROM OUTPUT OF FLEXIBILE JOINT ON SPACE ANTENNA TO POWER GRID INTERFACE

The chart shows the variation of equipment availability in the overall SPS power transfer system. If power recovery methods are used in the space antenna, then the output power at the power grid interface is determined by the equipment availability. Without power recovery (redirecting the available DC power for DC to RF conversion to the still available part of the space antenna radiating components) the available power at the utility interface is lower because a lost radiating component in the space antenna represents loss of power as well as loss of antenna area.

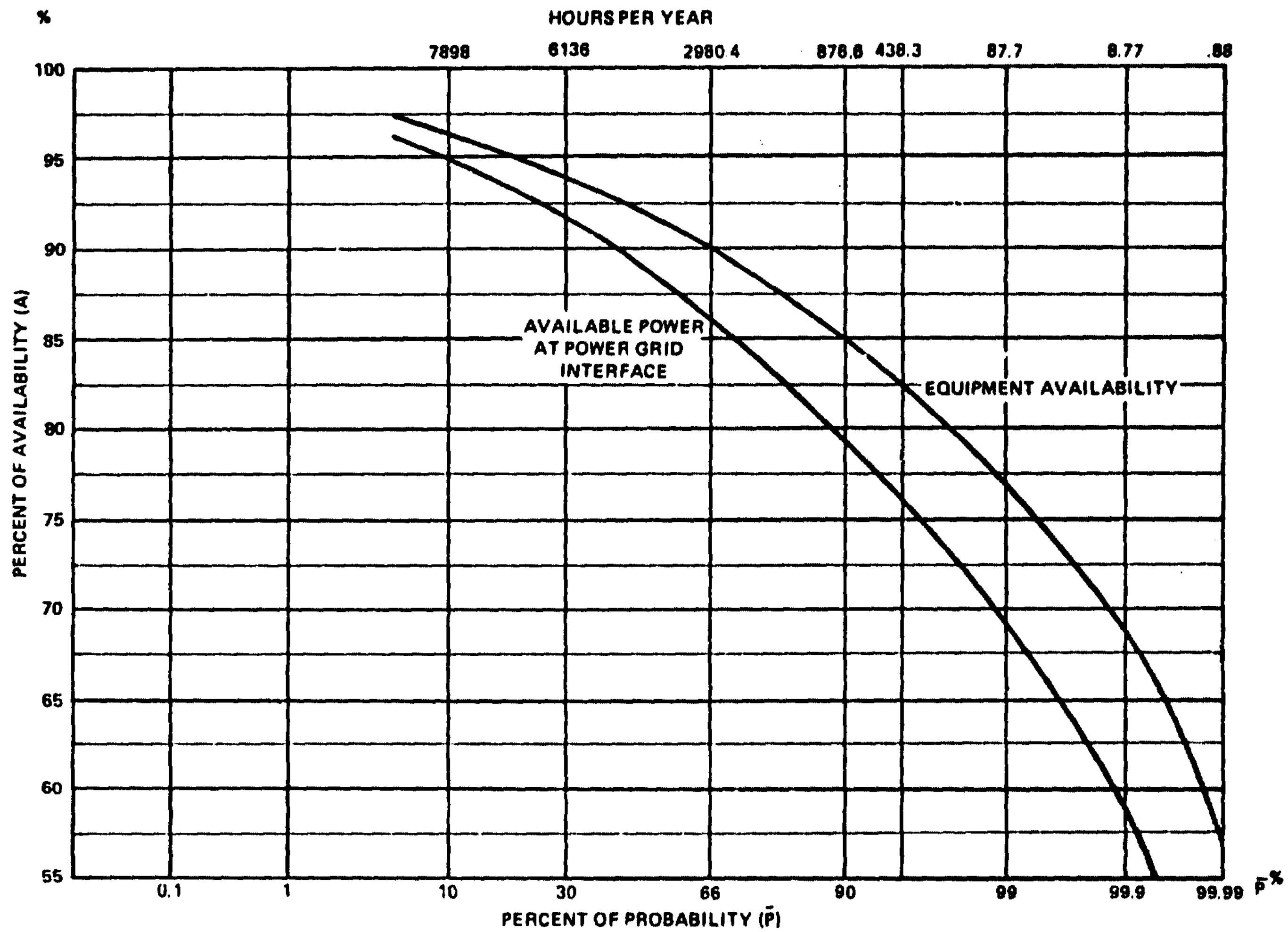
The mean availability for the two cases is approximately 90% and 86% respectively.

D180-25037-5

GENERAL ELECTRIC

space division

AVAILABILITY VS. PROBABILITY OF OVERALL SPS POWER TRANSMISSION SYSTEM FROM OUTPUT OF FLEXIBLE JOINT ON SPACE ANTENNA TO POWER GRID INTERFACE



SMALL SPS'S

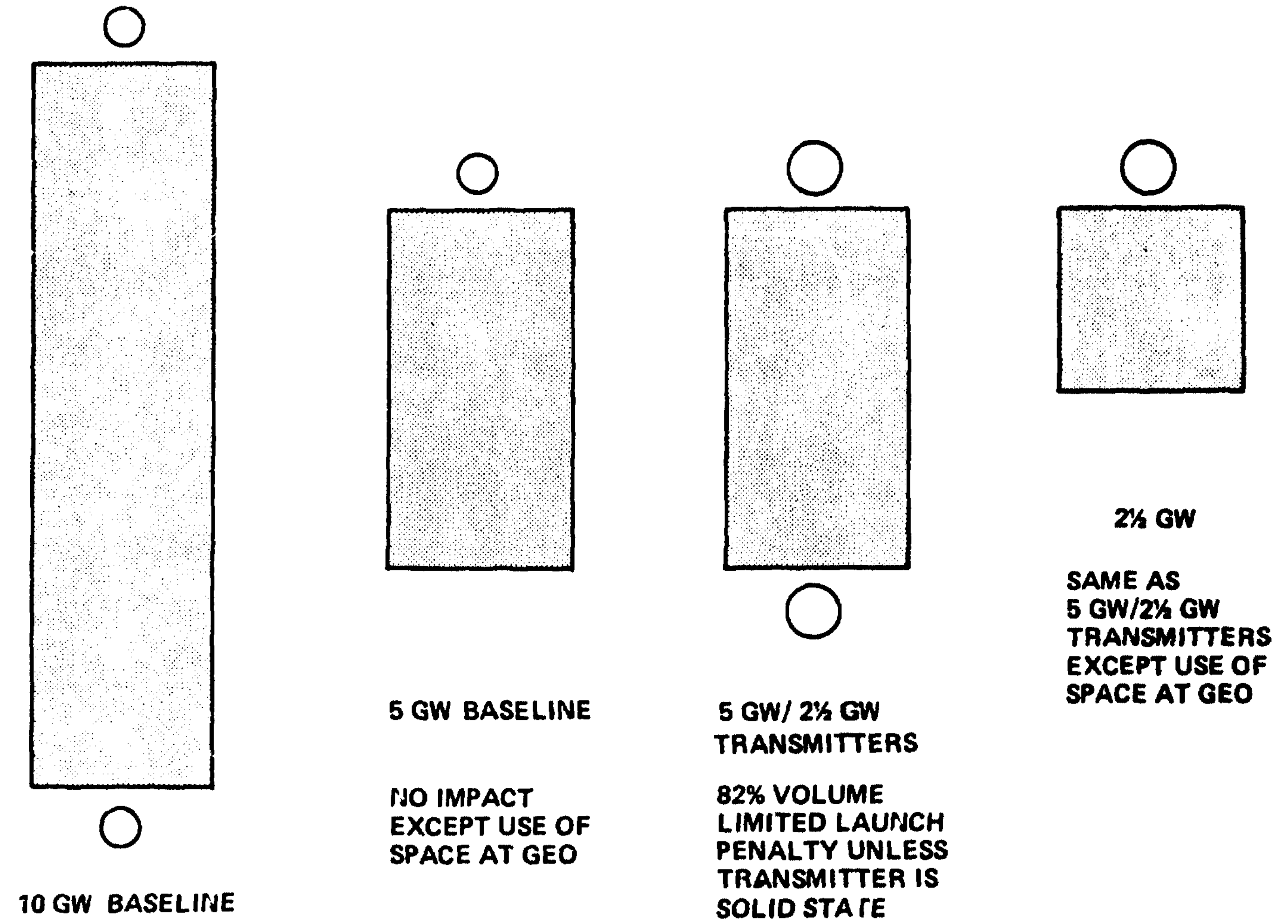
Smaller SPS configurations were compared to the original 10 gigawatt baseline. The first was the present NASA 5 gigawatt baseline with one transmitting antenna. Analysis of the control requirements for this asymmetric configuration determined that because of the overriding importance of solar pressure compensation in the control thrust scheme, no propellant penalties were incurred by the lack of symmetry. Also, no packaging differences have been identified that would arise from dividing the original configuration into two equal halves. Therefore, the only consequence of this alternative to the original baseline is the requirement for more positions in geosynchronous orbit to effect a given total installed generating capacity.

The next alternative was also a five gigawatt system, but the power was divided into two power transmission links each rated at 2½ gigawatts. In order to minimize land use and rectenna costs, it is desirable when reducing the link power to increase the transmitter aperture, in turn reducing the receiving station area. This design option, however, has approximately 4 times as many transmitter subarrays as the single-transmitter 5 gigawatt satellite. As a result, it incurs a significant payload packaging problem because of the low packaging density of completely assembled transmitter subarrays. The packaging density situation appears to be much improved through use of a solid state transmitter. In the solid state option all of the active functions are included in a planar sheet only about 2 centimeters thick (including the resonant cavities). Thus, a much higher packaging density per unit of aperture area can be achieved.

The final option, like the second option, results from effectively dividing a symmetric configuration in half. As for the other case, no penalties were determined for this design option excepting the use of more geosynchronous orbit space.

Small SPS's

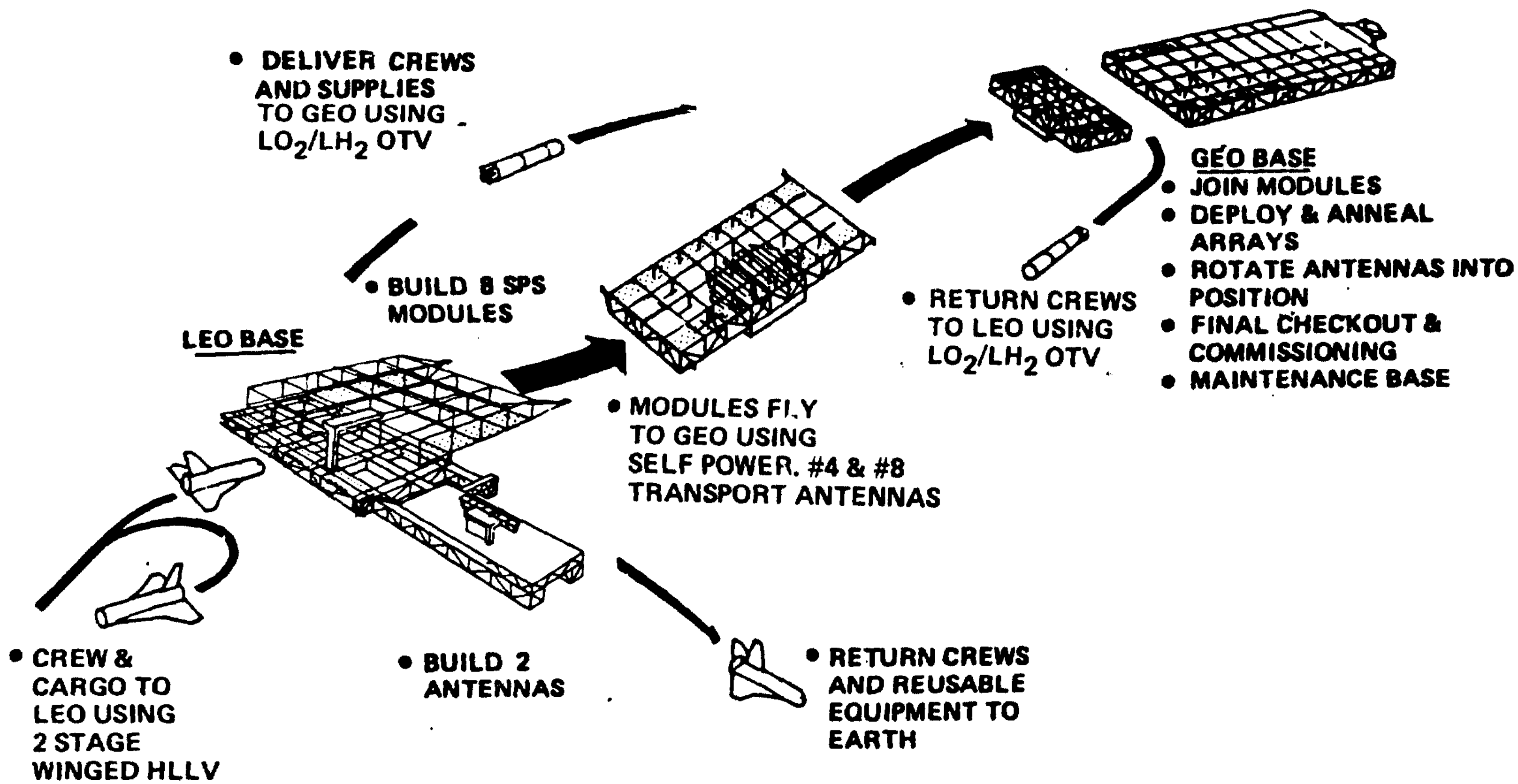
SPS-2251



LEO CONSTRUCTION CONCEPT SELF POWER MODULES

The preferred orbit to orbit transportation concept identified in the previous study was the use of electric propulsion systems to convert SPS modules into powered spacecraft that could transfer themselves to geosynchronous orbit with a trip time of approximately 150 days. A tradeoff study comparing this to construction of SPS at geosynchronous orbit with chemically-fueled (LO_2/LH_2) orbit transfer vehicles showed a cost saving of roughly $2 billion per 10,000 megawatt SPS. Variations on the basic self-power concept illustrated on this slide include return of the orbit transfer hardware for reuse by either chemical or electric orbit transfer vehicle means.

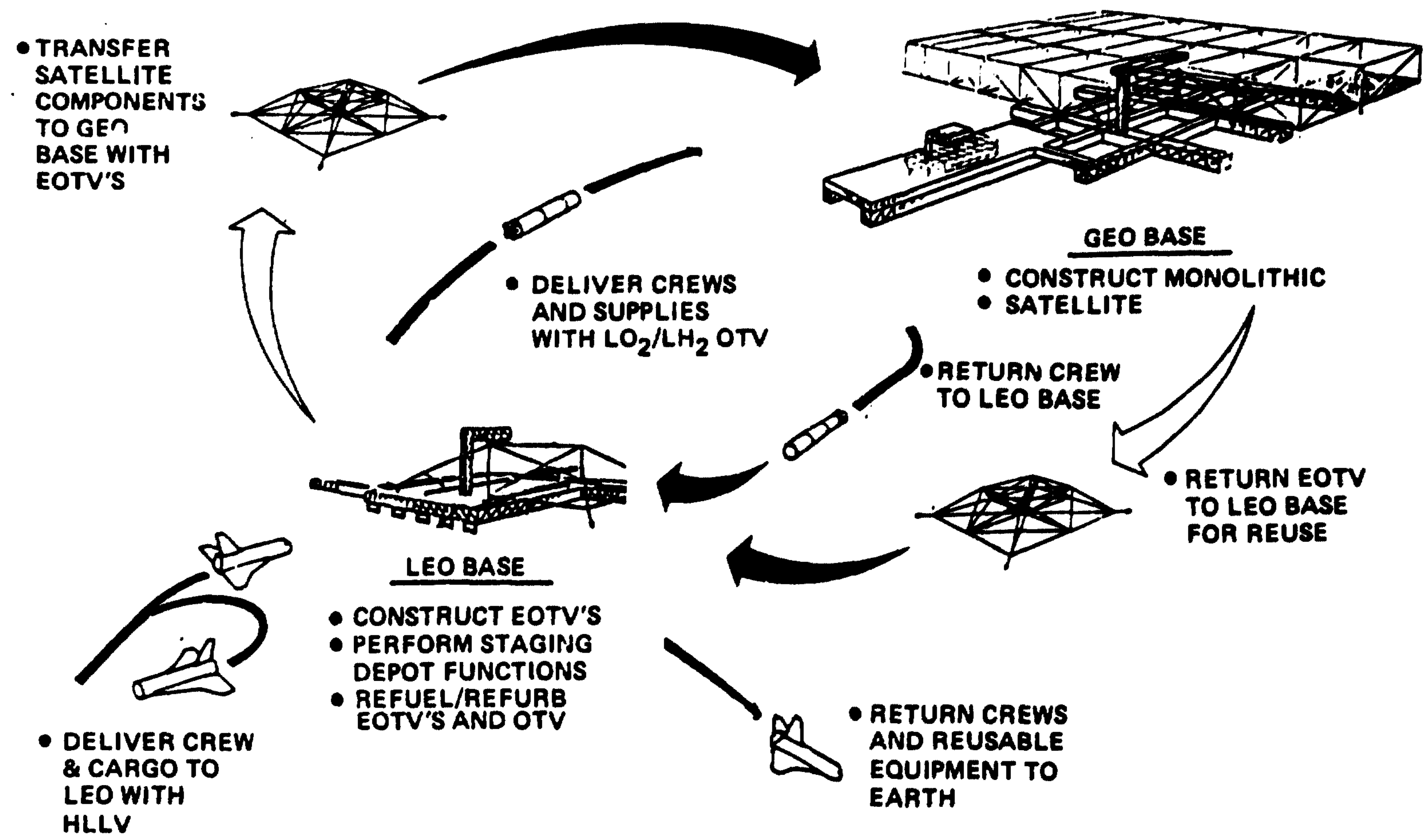
LEO Construction Concept
Self Power Modules



GEO CONSTRUCTION CONCEPT ELECTRIC ORBIT TRANSFER VEHICLES

During the present Phase I study, an analysis was conducted to evaluate the use of independent electric orbit transfer vehicles to allow the benefits of electric propulsion to be combined with the benefits of geosynchronous orbit construction. The operational concept is illustrated on the facing page. Electric orbit transfer vehicles are constructed in low earth orbit at a low earth orbit base which also provides staging depot functions. A fleet of approximately 20 electric orbit transfer vehicles conveys SPS payloads to geosynchronous orbit where SPS construction takes place. In order to provide expeditious transfers of crews and supplies, high thrust chemically-propelled orbit transfer vehicles are used to provide this service. The electric orbit transfer vehicles are reused 10 times over a lifetime of several years.

GEO Construction Concept
Electric Orbit Transfer Vehicles



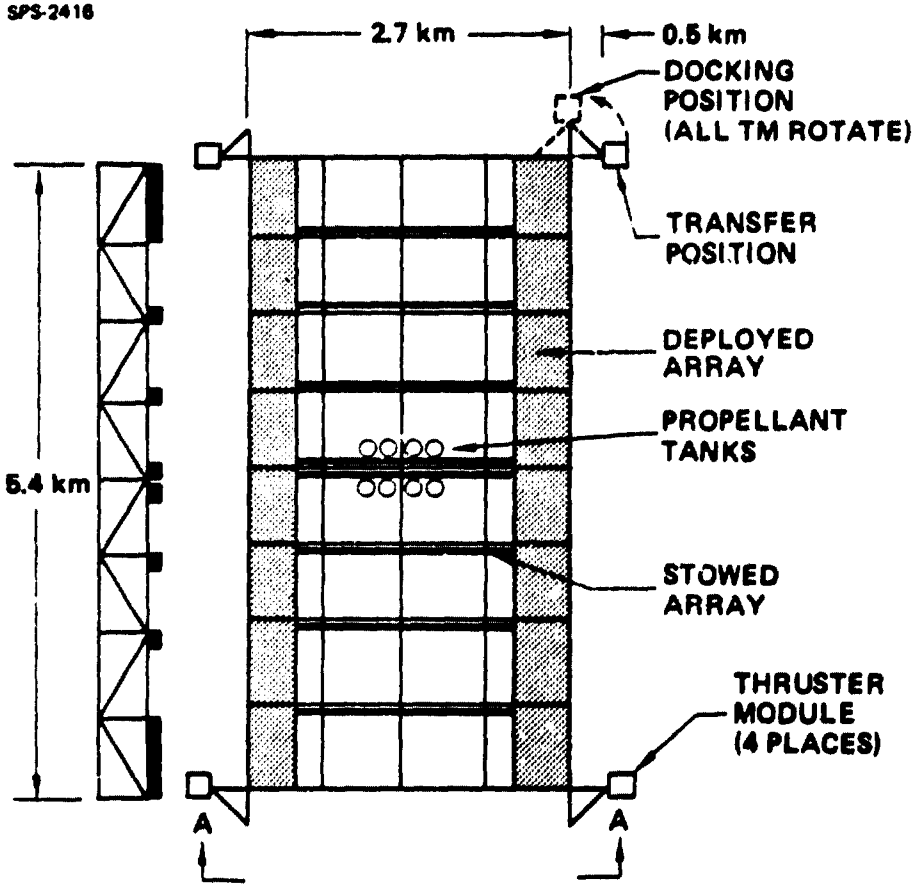
SELF-POWER CONFIGURATION PHOTOVOLTAIC SATELLITE

Several changes were made in the self-power configuration. The principal change was in the means of deploying the portion of the solar array to be used for orbit transfer. Deployment as illustrated makes three improvements over the earlier configuration: (1) Inertial balancing of the self-powered module is improved slightly; (2) Solar blanket stretching loads are eliminated from the structural beams that incur the highest load due to orbit transfer thrust forces; and (3) The problem of matching degraded solar cell arrays to undegraded arrays in a series connection is eliminated. This is quite important since current degradation due to radiation is more significant than voltage degradation.

A second change involves a relocation of the thruster modules to improve inertia balancing and thrust moment capability. Several propellant tank locations were tried to improve inertia balancing, with the final result being that location at the center of the module provides the best overall transfer performance. The result of these changes was an improvement in the effective average integrated specific impulse for self-power transfer from approximately 2100 seconds to approximately 3000 seconds. The electric specific impulse used is 7,500 seconds, but this is significantly degraded by the use of chemical thrust during occultations periods and to control high gravity gradience during the early part of the transfer. (In comparison the net integrated average specific impulse for the independent electric OTV is approximately 6,000 seconds. This higher performance results because the electric OTV is considerably smaller than the self-power module and does not suffer very much from gravity gradience performance degradation.)

Self-Power Configuration Photovoltaic Satellite

SPS-2416

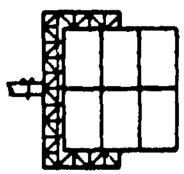


GENERAL CHARACTERISTICS

- 3% oversizing (radiation)
- Trip time = 140 days
- I_{SP} = 7,000 sec

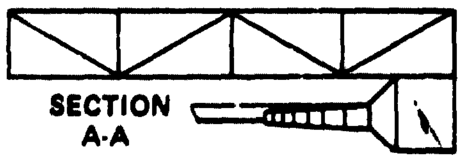
MODULE CHARACTERISTICS	NO ANTENNA	WITH ANTENNA
• Number of modules	6	2
• Module mass (10^6 kg)	8.7	23.7
• Power required (10^6 kW)	0.3	0.81
• Array (%)	13	36
• OTS dry (10^6 kg)	1.1	2.9
• Argon (10^6 kg)	1.0	5.1
• LO_2/LH_2 (10^6 kg)	1.4	2.2
• Electrical thrust (10^3 N) [1]	4.5	12.2
• Chemical thrust (10^3 N)	12.0	8.0

[1] 20% additional thrust available for GGT and thrust vector control



	NO ANTENNA	ANTENNA
Panel size:	24x38m	48x57m
Thrusters:	600	1,600

MODULE WITH ANTENNA



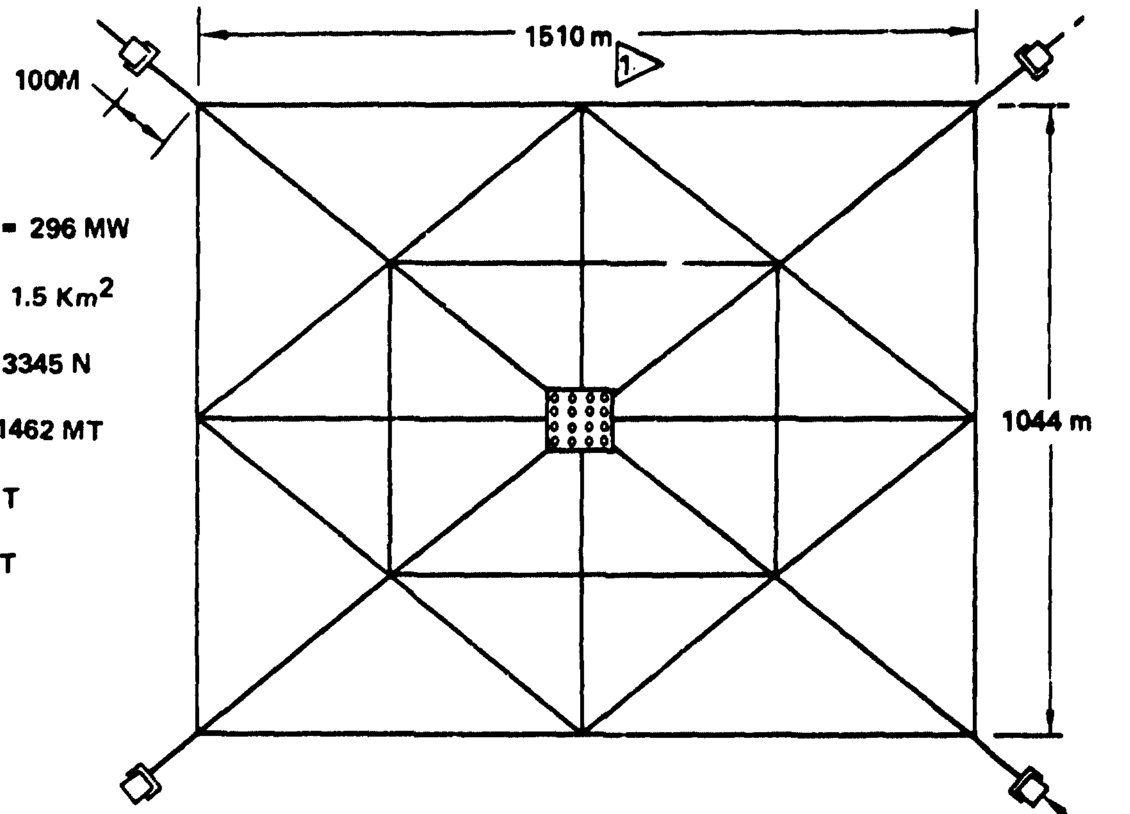
EOTV CONFIGURATION

The independent electric OTV configuration shown here is updated from earlier mid-term data. Mass and size increases resulted from incorporation of bussing losses in the power budget and correction of other analysis approximations used in the earlier effort. This orbit transfer vehicle is sized to deliver 4,000 metric tons to geosynchronous orbit and return with 200 metric tons. The return payload capability provides for return of packaging equipment and other items from the geosynchronous orbit construction site. Because the electric orbit transfer vehicle is smaller than the SPS modules discussed on the previous page, it suffers comparatively little from performance losses induced by gravity gradients.

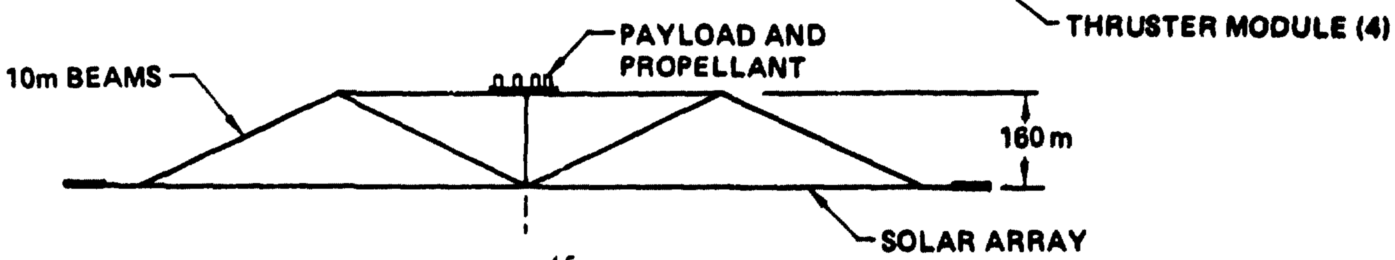
Electric OTV Configuration

SPS-2423A

- INITIAL POWER = 296 MW
- ARRAY AREA = 1.5 Km^2
- ELEC THRUST = 3345 N
- EMPTY MASS = 1462 MT
- ARGON = 469 MT
- LO_2/LH_2 = 46 MT



- PAYLOAD
  UP = 4000 MT
  DOWN = 200 MT
- TRIP TIME:
  UP = 180 DAYS
  DOWN = 40 DAYS
- I_S = 8,000 sec



ORBIT TRANSFER SYSTEM COST COMPARISONS

A comprehensive cost comparison was developed in order to show the contrast between the self-powered electric propulsion option and the independent electric orbit transfer vehicle. Included in this comparison are the differences in costs of construction operations. Three systems are compared: (1) the use of electric propelled SPS self-transport modules without recovery of the electric propulsion equipment; (2) the self-propelled option with the use of small electric OTV's to recover the orbit transfer hardware; (3) the use of independent electric orbit transfer vehicles for all orbit-to-orbit cargo transportation with construction of SPS's at geosynchronous orbit.

The bars on the left show the total cost of preparing to carry out the construction operations including the unit cost of the construction bases and of their transportation. The second set of bars shows the transportation system fleet investment required to establish a production rate of 10,000 megawatts per year. The third set of bars shows the cost of transportation operations for the first year's operations, i.e., construction of two 5,000 megawatt SPS's. The fourth set of bars is simply the sum of the first three sets showing the total transportation and construction system cost that must be invested through the first year's production operation. The fifth set of bars shows fully amertized costs for the three systems including amortization of all capital investments at an interest rate of 7½%.

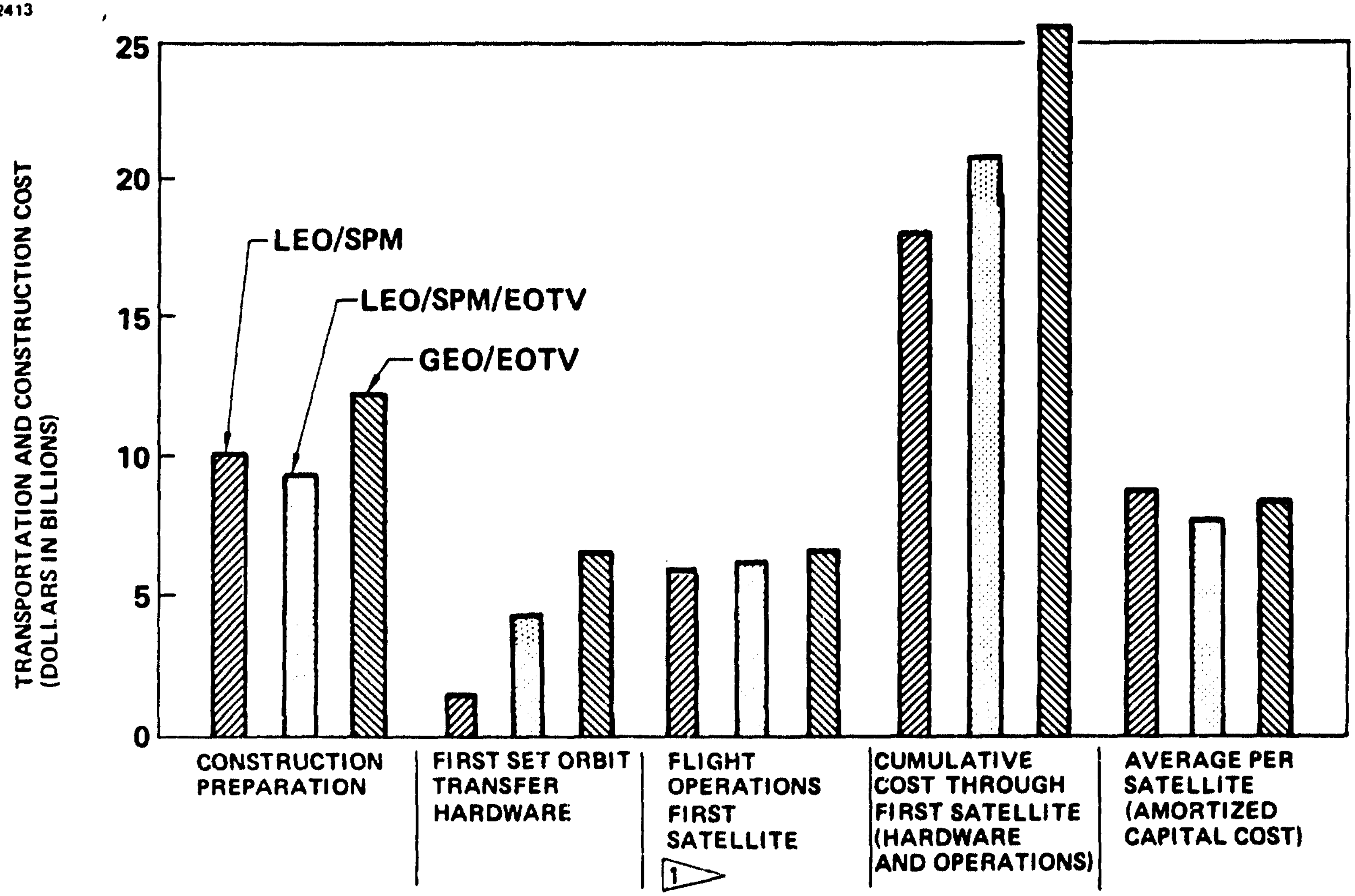
The greater capital cost of the independent electric orbit transfer vehicle system is offset by its reduced fuel consumption on a fully amortized basis. However, the difference in front end cost to establish a production rate of 10,000 megawatts per year is quite significant, approximately $7 billion.

SPS

Construction/Transportation Cost Comparison

BOEING

SPS-2413



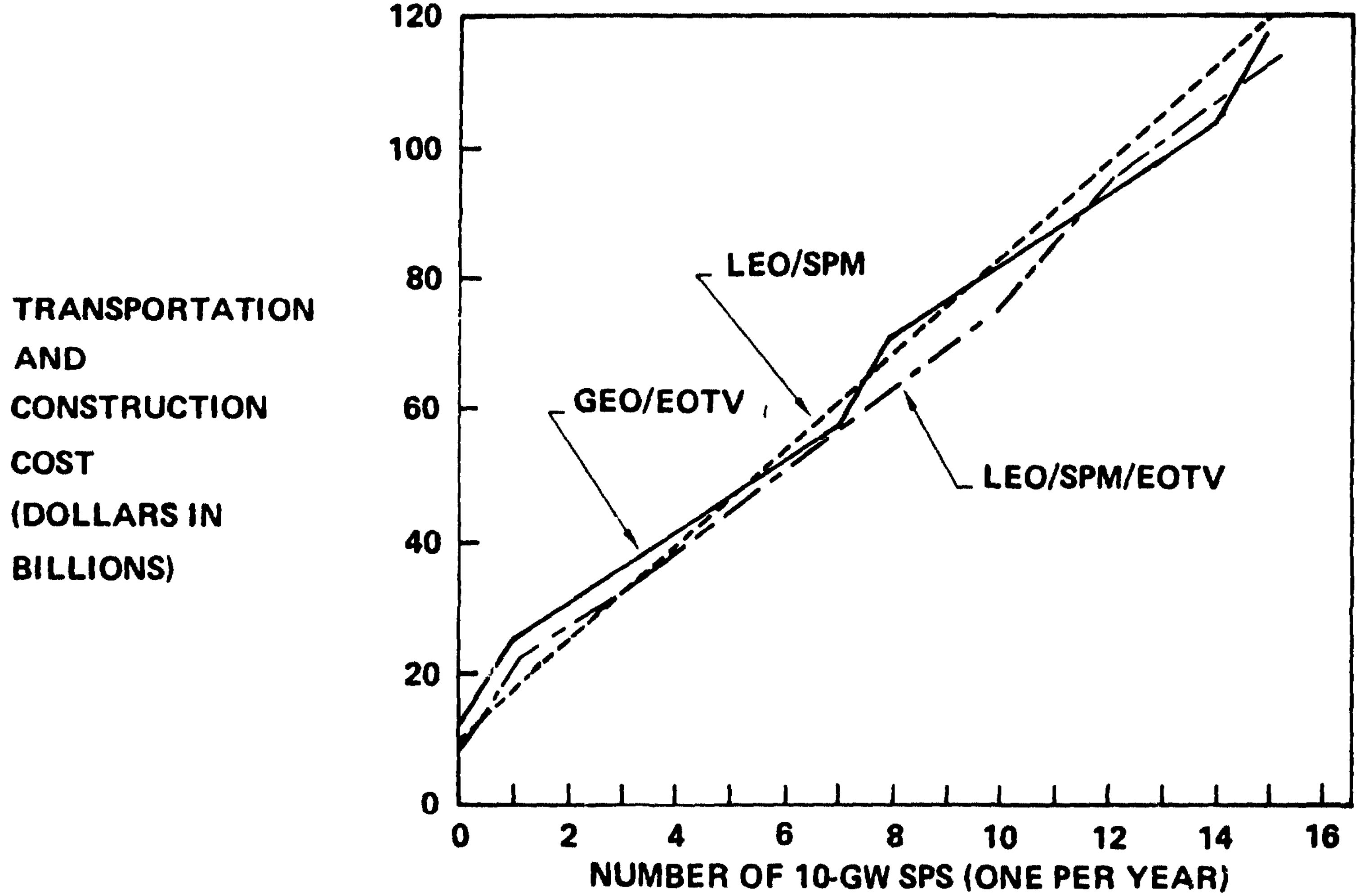
1 Satellite(s) producing 10 GW

CUMULATIVE COST COMPARISON

Cost trends with time for the three orbit transfer/construction location options are shown here.

Cumulative Cost Comparison

SPS-2412



CONSTRUCTION LOCATION SUMMARY

Summarized here are the important comparison factors for low earth orbit construction with self-power of the SPS modules to geosynchronous orbit and construction at geosynchronous orbit using independent electric orbit transfer vehicles for transfer operations. A qualitative preference is indicated for construction in low earth orbit.

Construction Location Summary

SPS-2486

COMPARISON PARAMETER	① LEO/SPM	② LEO/SPM/EOTV	③ GEO/EOTV	RATIONALE
• CONST PREPARATION	• NO SIGNIF DIFF			• SAME TIME FOR FIRST SATELLITE
• SATELLITE DESIGN IMPACT			✓	• NO MODULARITY • SMALLER LOADS
• ORBITAL BASES/CONST EQUIP	• NO SIGNIF DIFF			• SAME CONST BASE • STAGING DEPOT VS FINAL ASSY BASE
• CONSTRUCTION OPS			✓	• NO MODULE BERTHING OR ANTENNA HINGING
• CREW REQ'TS	✓			• SAME SIZE BUT MAJORITY AT LEO
• ENVIRONMENTAL FACTORS	• NO SIGNIF DIFF			• ALL CAN BE HANDLED WITH ACCEPTABLE SOLUTIONS
• ORBIT TRANSFER OPS	✓			• FEWER POTENTIAL COLLISIONS AND BEAM PENETRATIONS
• LAUNCH OPS	• SO SIGNIF DIFF			• APPROX SAME NO. LAUNCHES
• RISK/UNCERTAINTY	✓			• MULTI USE IN HOSTILE ENVIRONMENT NOT REQ'D
• CONST COST	✓	✓		• CHEAPER ≈ $2B
• FIRST SAT. TRANS COST	✓			• CHEAPER $3B OVER ② $7B OVER ③
• AVG. COST PER SAT		✓	✓	• CHEAPER ($0.6B)

✓ INDICATES MOST PROMISING

ORBIT TO ORBIT TRANSPORTATION CONCLUSIONS

Self-power from low earth orbit construction bases for establishment of SPS's at geosynchronous orbit is recommended as the preferred approach. This preference arises primarily because of the significant difference in front end cost. The independent electric orbit transfer vehicle may show a slight cost advantage amortized over a large production run. This cost advantage is sensitive to radiation degradation effects. If the independent electric orbit transfer vehicle can be reused many times by successful annealing of its solar blankets, it can provide low cost. If annealing recovery is less complete, the sel.-power operations which expose solar arrays to the orbit transfer radiation degradation only once, will exhibit lower cost.

A further sensitivity issue is hardware cost uncertainties. The independent electric orbit transfer vehicle (with the nominal reuse scenario developed under this study) shows relatively little sensitivity to hardware cost because the cost of the orbit transfer hardware is amortized over several SPS's.

Gallium arsenide solar blankets for the independent electric OTV were also examined. No advantage was found for the use of gallium arsenide in the orbit transfer vehicles under the assumption that silicon was to be used for the satellite systems. Clearly, if gallium arsenide is to be used for the SPS then it makes sense to also use it for the orbit transfer system.

Orbit-to-Orbit Transportation Conclusions

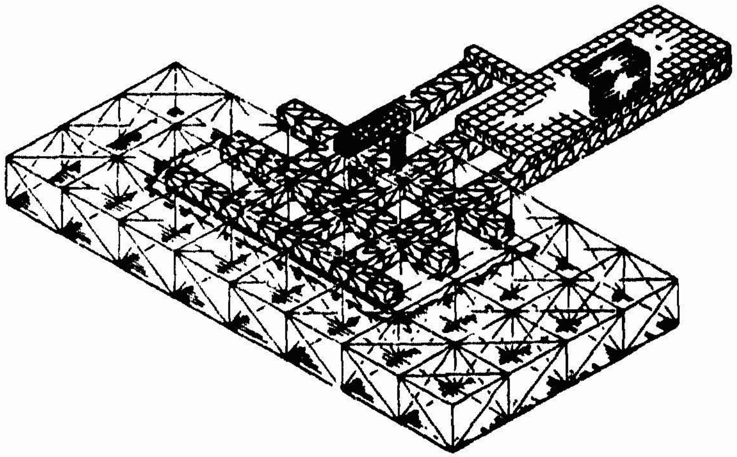
SPS 2433

- RECOMMEND SELF-POWER, LEO CONSTRUCTION
- SELF-POWER HAS SIGNIFICANT FRONT-END COST ADVANTAGE ($\approx$ \$7 BILLION) COMPARED TO IEOTV
- IEOTV MAY HAVE SLIGHT COST ADVANTAGE WHEN AMORTIZED OVER 150 OR MORE GIGAWATTS OF SPS CAPACITY
- SELF-POWER OPERATIONS NOT DEPENDENT ON MULTIPLE REUSE OF HARDWARE REPEATEDLY EXPOSED TO TRANSFER ENVIRONMENT
- IEOTV IS LESS SENSITIVE TO HARDWARE COST UNCERTAINTIES
- NO ADVANTAGE FOR GALLIUM ARSENIDE

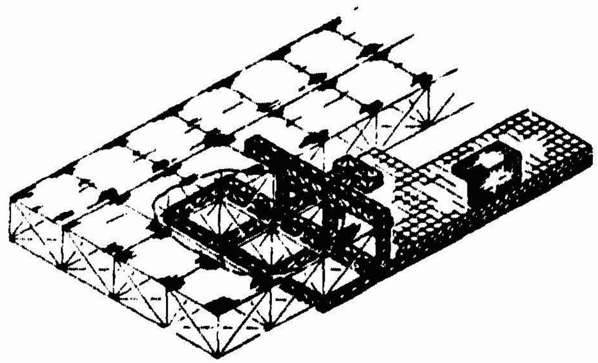
ALTERNATE CONSTRUCTION BASE CONCEPTS

During the Phase I activity, a variety of construction base concepts were developed and narrowed to two principal contenders by the mid-term. These were (1) a platform or single-deck construction system, and (2) an end builder. The two are shown on the facing page. In the case of the platform facility, construction of structure and installation of solar arrays and subsystems takes place on separate parts of the facility with a maximum of uncoupling of operations. The end builder installs solar arrays simultaneously with construction of structure and the SPS moves away from the construction facility in a continuous manner as construction takes place. The systems were compared and evaluated for geosynchronous orbit construction. The construction rate was set to build a 5,000 megawatt monolithic SPS in a 180-day period. The antenna construction facility was not a variable in this analysis.

ALTERNATE CONSTRUCTION BASE CONCEPTS



SINGLE DECK
(WITH CONSTRUCTION GANTRY)



END BUILDER
2 BAY $

- GEO CONSTRUCTION
- 5GW MONOLOTHIC SPS
- 180 DAY CONSTRUCTION TIME
- SAME ANTENNA CONSTRUCTION FACILITY

2935-080V

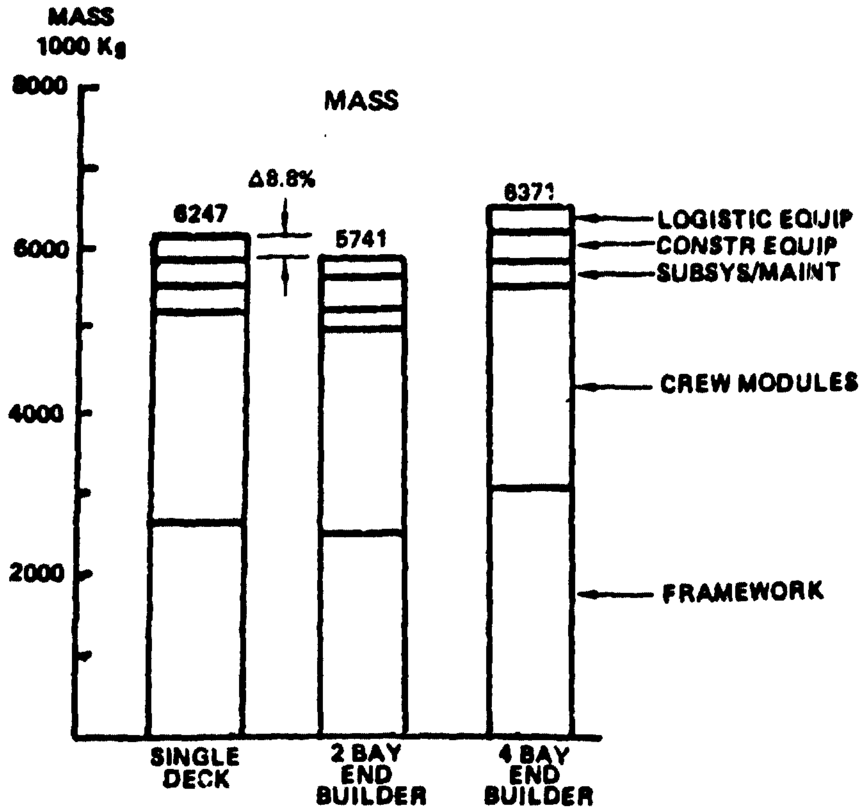
ALTERNATIVE CONSTRUCTION CONCEPTS

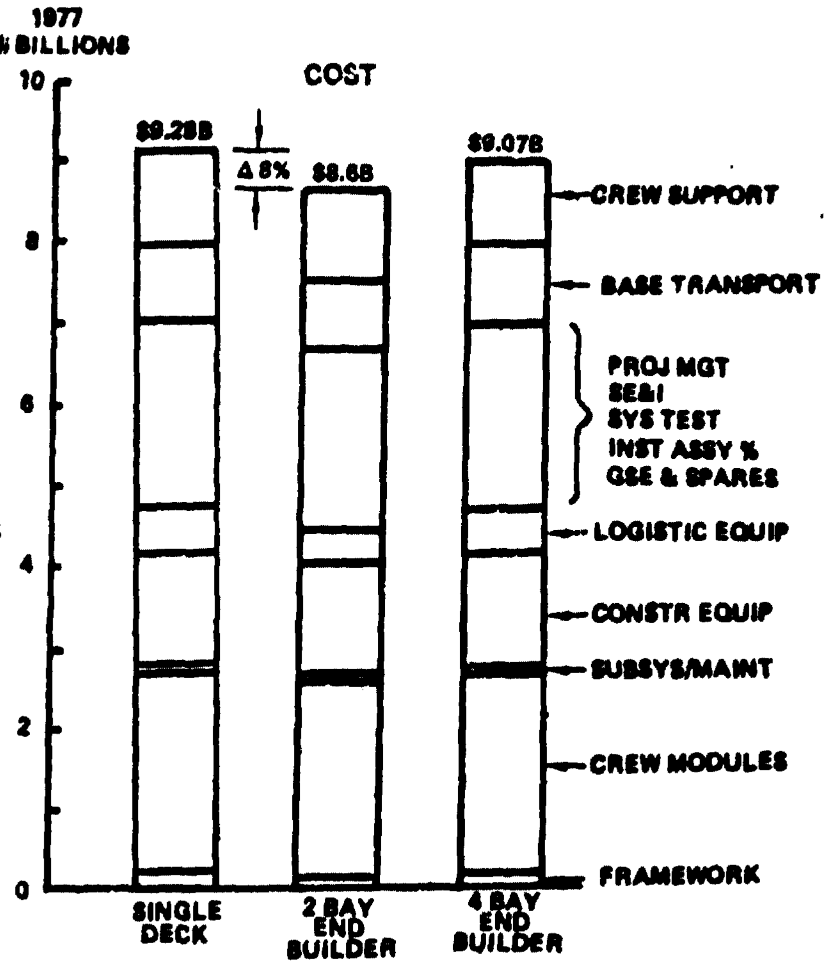
MASS AND COST COMPARISON

As can be seen in this figure, the mass and cost estimates for the three candidates turn out to be very close, subsequently, the selection of the preferred approach will be determined by other criteria.

Alternative Construction Concepts Mass & Cost Comparison

SPS-2436





ALTERNATE CONSTRUCTION CONCEPTS SUMMARY

This table summarizes the differences between the three concpets. The essence of this comparison is that the Single Deck facility incorporates less complex construction operations and is more adaptable to SPS design changes after the base is constructed and the End Builders have an inherent capability for higher production rates.

Alternate Construction Concepts Summary

CRITERIA	SINGLE DECK	2-BAY END BUILDER	4-BAY END BUILDER
BASE COST	\$9.28B	\$8.6B	\$9.07B
BASE MASS	6247×10^6 kg	5741×10^6 kg	6371×10^6 kg
CREW SIZE	407	385	387
OPERATIONS COMPLEXITY	DECOUPLED STRUCTURE ASSY/ SOLAR ARRAY DEPLOY	COUPLED STRUCTURAL ASSY/ SOLAR ARRAY DEPLOY	COUPLED STRUCTURAL ASSY/ SOLAR ARRAY DEPLOY
FLEXIBILITY (AFTER BASE BUILT)			
• HIGHER RATES		FASTER RATE CAPABILITY INHERENT	FASTER RATE CAPABILITY INHERENT
• FRAME DESIGN CHANGES	EASIER TO ADAPT		
• BAY SIZE CHANGE	EASIER TO ADAPT		
DEVELOPMENT RISK	NO SIGNIFICANT DIFFERENCE		

CONCLUSIONS FROM CONSTRUCTION METHODOLOGY EVALUATION

Principal conclusions from this evaluation are presented on the facing page.

Conclusions from Construction Methodology Evaluation

- BEST APPROACH IS TO EVOLVE FROM PLATFORM TO END-BUILDER WHEN WARRANTED BY PROGRAM MATURITY AND PRODUCTION RATE
- PLATFORM IS MORE FLEXIBLE
  - ADAPTS EASIER TO SPS CONFIGURATION CHANGES
  - MORE TOLERANT OF EQUIPMENT BREAKDOWN & SCHEDULE ANOMALIES
- PLATFORM IS BEST FOR PROTOTYPE PHASE
- END-BUILDER AND PLATFORM (SINGLE-DECK) BASES ARE SIMILAR IN CONFIGURATION AND FEATURES
- END-BUILDER HAS EVENTUAL HIGHER PRODUCTIVITY AND SLIGHTLY LOWER COST AT MODERATE TO HIGH PRODUCTION RATES
- COMPARISON IS NOT AFFECTED BY LEO/GEO ISSUE

LAUNCH SITE SELECTION

The launch site analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages with respect to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30^{0} inclination orbit. With a 30^{0} inclination orbit for staging or construction operations, a 30^{0} plane change is required to reach a geosynchronous equatorial orbit. It was presumed that this plane change would incur significant performance penalties relative to a zero-degree or low-inclination low earth orbit. However, with electric propulsion this performance difference in terms of cost is minimal. Therefore, the principal motivation for leaving KSC for a remote site will stem from the eventuality of SPS operations outgrowing KSC. Our estimates to date indicate that KSC can handle approximately 10 gigawatts per year of SPS construction.

Remote site options include land-based sites such as the mouth of the Amazon in Brazil and ocean-based sites employing large floating structures such as the western Pacific low latitude sites identified by Jim Akkerman in studies at the Johnson Space Center. Large uncertainties presently exist as to the cost of large floating structures. The two orders of magnitude range is indicated on the facing page.

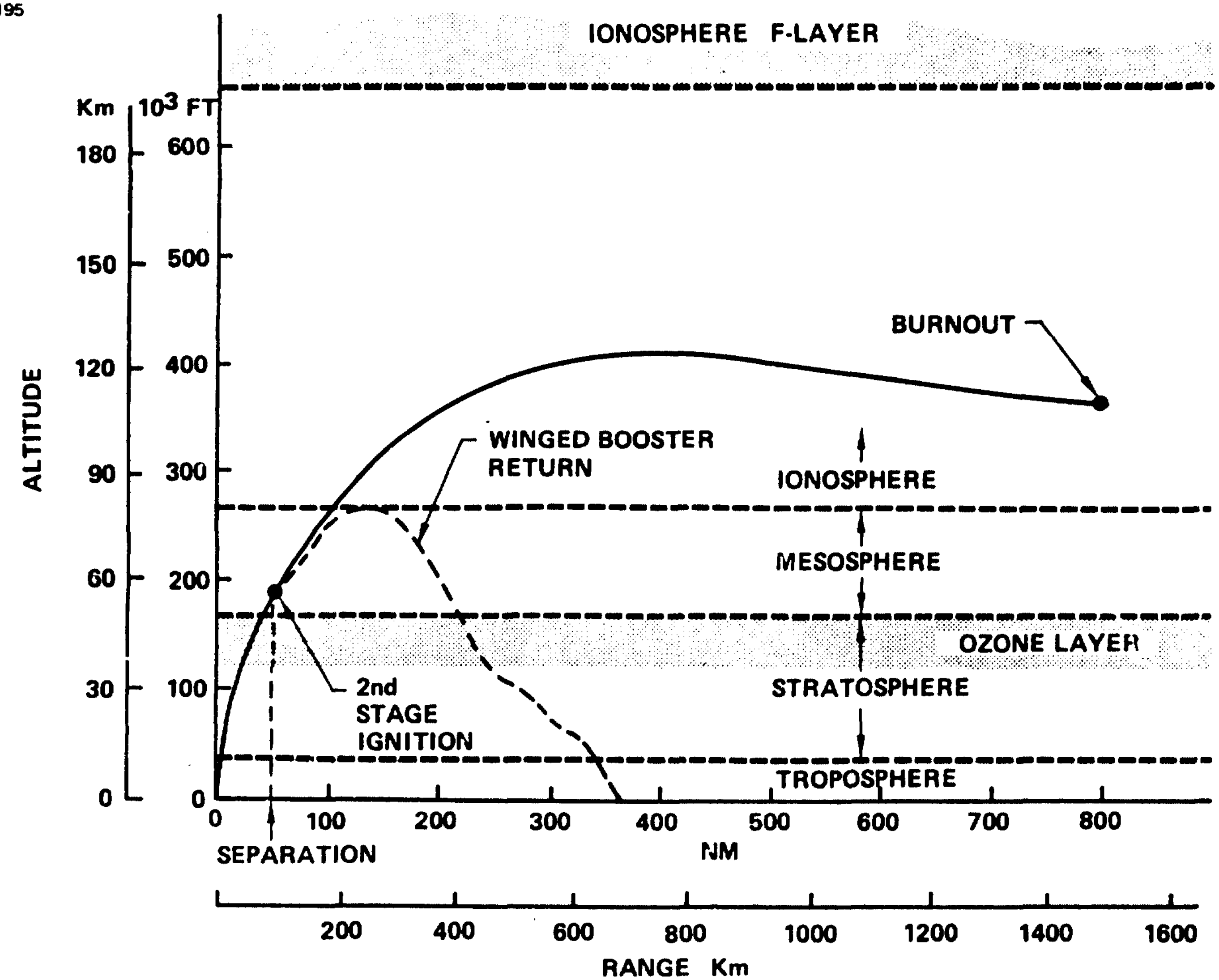
Launch Site Selection

- PERFORMANCE ADVANTAGE FOR LOW LATITUDE IS SMALL ($<10\%$) FOR ELECTRIC PROPULSION
- PRINCIPAL MOTIVATION FOR REMOTE SITE WILL OCCUR IF SPS OPERATIONS OUTGROW KSC
- KSC APPEARS SUITED FOR ABOUT 10GW/YEAR
- OCEAN SITE POTENTIALLY ATTRACTIVE DEPENDING ON COST OF LARGE FLOATING STRUCTURES
  - AIRCRAFT CARRIERS $\sim \$50\,000/\text{M}^2$
  - DRYDOCKS & BARGES $\sim \$5\,000/\text{M}^2$
  - CONCRETE FLOATS $< \$500/\text{M}^2$ (HOUSEBOATS)

REFERENCE HLLV LAUNCH TRAJECTORY

One of the environmental issues raised with respect to SPS operations is the possibility of influences on the upper atmosphere from launch operations. This figure shows the relationship of the current baseline trajectory to the key regions of the upper atmosphere.

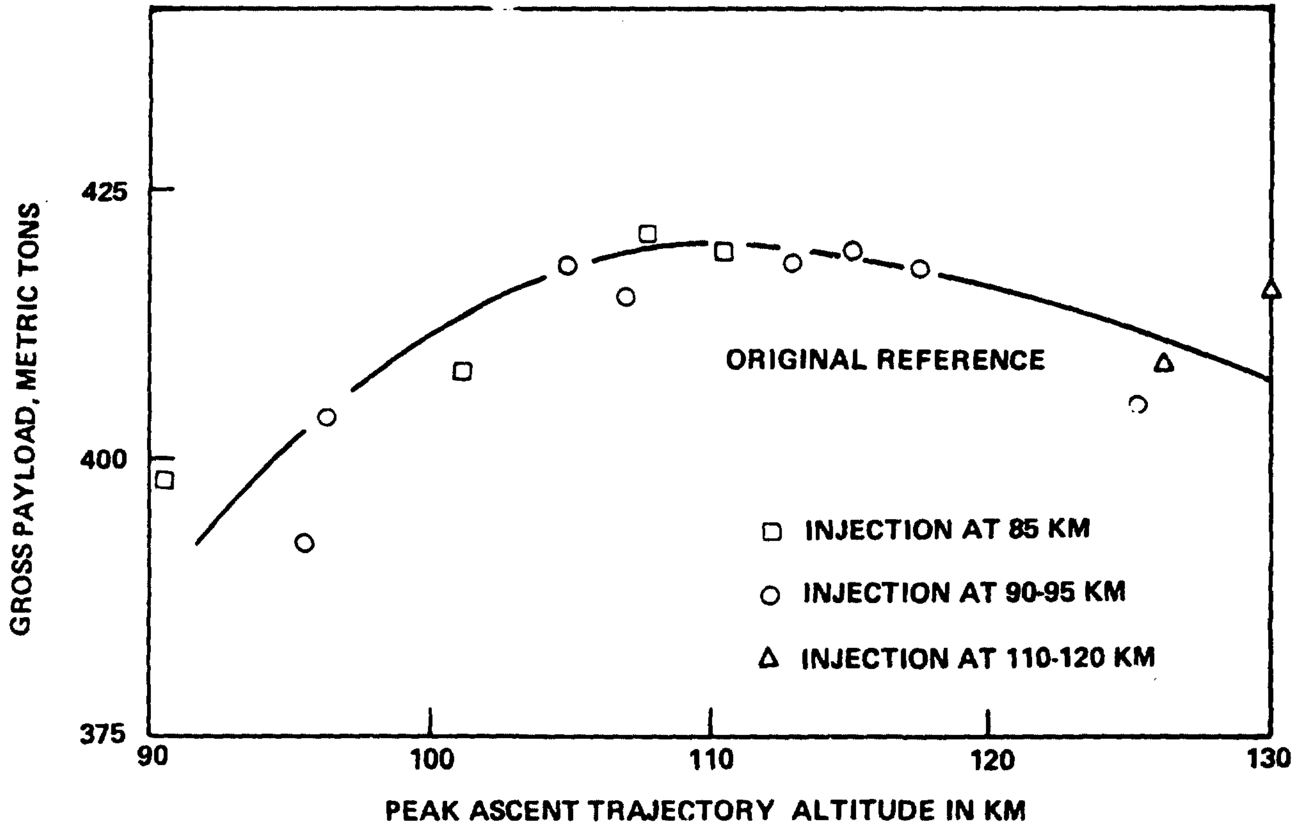
Reference HLLV Launch Trajectory



LAUNCH TRAJECTORY SUPPR SION RESULTS

A number of ascent trajectories were simulated using various strategies to minimize trajectory altitude. Results are summarized on the facing page. It was found that the best trajectories had a peak ascent altitude of about 110 kilometers. Trajectories could be suppressed to keep the path below 100 kilometers with a slight performance penalty.

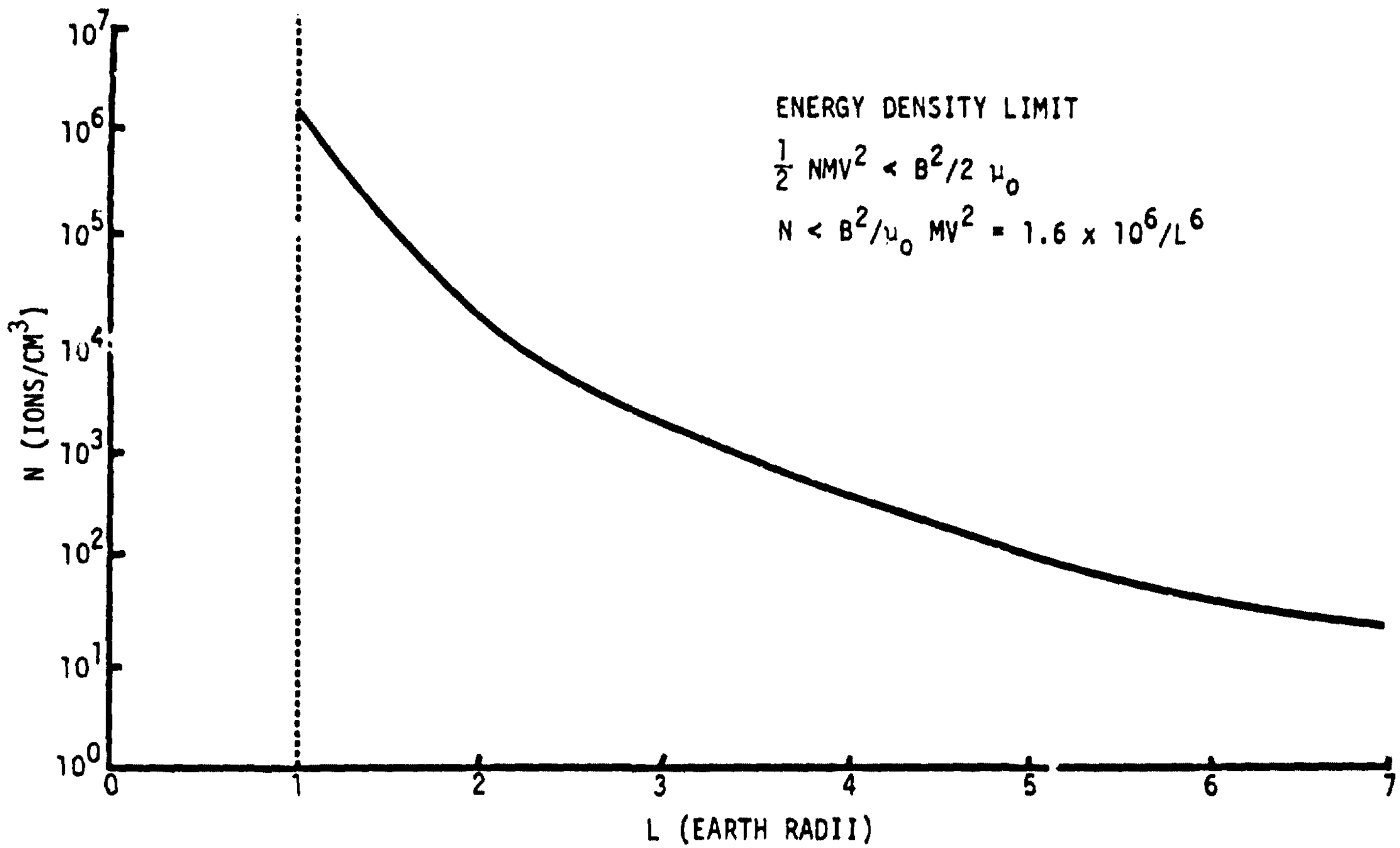
Launch Trajectory Suppression Results



GEOMAGNETIC FIELD CAPACITY TO CONFINE SPS ION THRUSTER PLASMA

Ion thrusters used for electric orbit transfer will emit large numbers of positively charged argon ions and negatively charged electrons. As these beams of particles leave the vicinity of the SPS or orbit transfer vehicle and diffuse to lower densities they will become geomagnetically trapped in the earth's magnetic field. Shown on the facing page is the capability of the magnetic field to confine plasma from the ion thrusters based on ion energies of about 1500 electron volts.

GEOMAGNETIC FIELD CAPACITY TO CONFINE SPS ION THRUSTER PLASMA (1.5 keV ARGON)

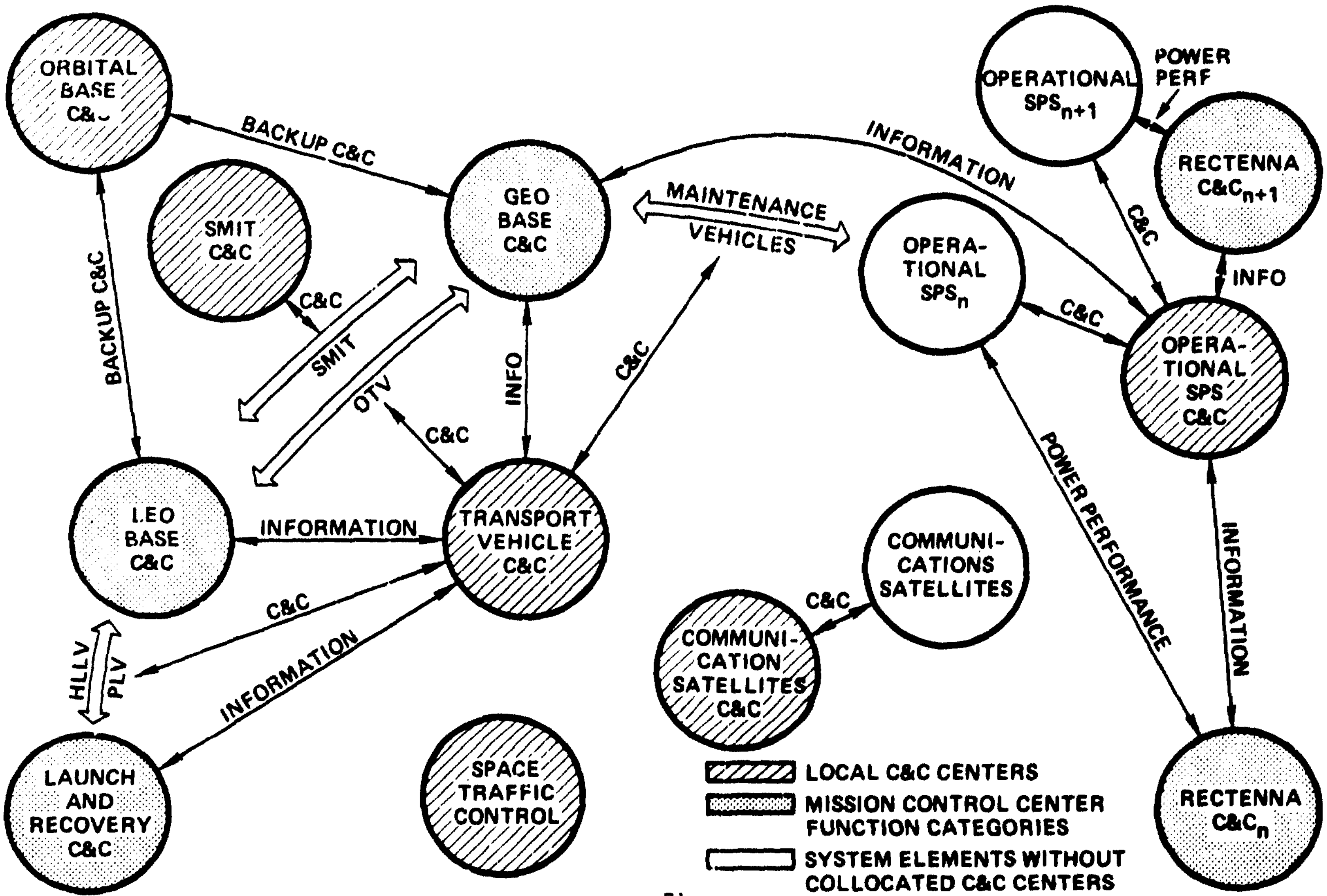


COMMAND CONTROL CENTER RELATIONSHIPS TO MAJOR SYSTEM ELEMENTS AND TO EACH OTHER

As a part of the phase I activity it was desired to develop a concept for mission control operations to enable studies of mission operations in the phase II activity. Several concepts were considered and the organization shown on the facing page selected for the phase II analysis.

TRW
DEFENSE AND SPACE SYSTEMS GROUP

C&C CENTER RELATIONSHIPS TO MAJOR SYSTEM ELEMENTS AND TO EACH OTHER



INDUSTRIAL INFRASTRUCTURE

A preliminary analysis of the industrial infrastructure was conducted with results as indicated on the facing page. *Of the several components that require production rates significantly higher* than those in present industrial experience,only the solar blankets represent a significant problem. Production rates of SPS hardware are, in general, not high when compared to production rates in major U.S. industries. The solar blankets represent a significant problem because major technological advances in production techniques must be accomplished in order to meet the production demands of an SPS system.

Industrial Infrastructure

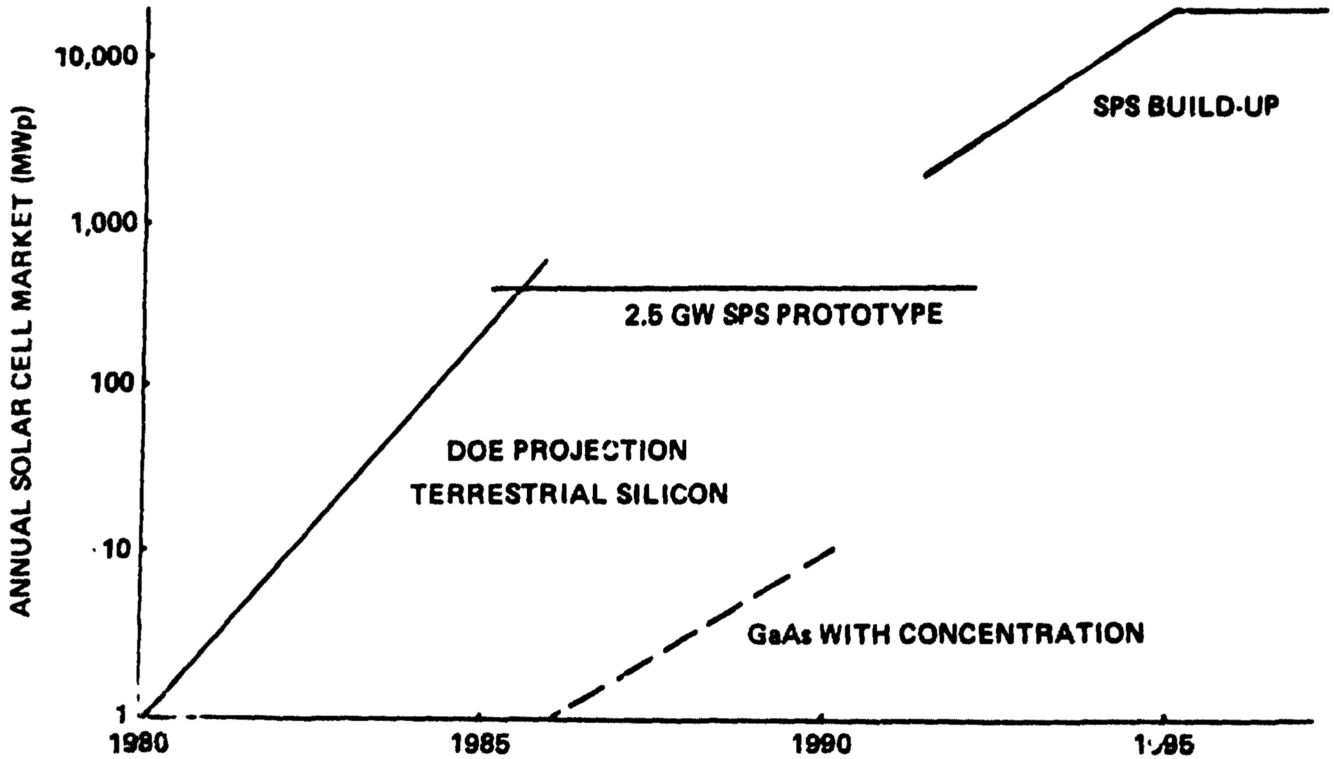
- SEVERAL COMPONENTS REQUIRE PRODUCTION RATES GREATER THAN PRESENT CAPABILITY
  - SOLAR BLANKETS
  - GRAPHITE STRUCTURE
  - KLYSTRONS
  - ELECTRIC THRUSTERS
  - LIQUID HYDROGEN
- ONLY SOLAR BLANKETS REPRESENT A PROBLEM

TERRESTRIAL AND SPS PHOTOVOLTAIC MARKET GROWTH SCENARIO

Arthur D. Little's analysis of the photovoltaic market growth shows that the production rates of solar cells to enable an SPS prototype program are within the range expected for the Department of Energy Terrestrial Silicon Program. Differences between terrestrial and space solar cells may be significant, but much of the production technology for the terrestrial program will be applicable to SPS. Further in the future, the buildup of production capability to support an SPS production program of 10,000 megawatts per year will require production rates much higher than those for the prototype system. Solar blankets for the prototype can be accumulated over several years to minimize the production capacity required, whereas the production capability for a commercial SPS program must match the installation rate.

Terrestrial and SPS Photovoltaic Market Growth Scenarios

SPS-2634



NEW SOLAR POWER SATELLITE PROGRAM WORK BREAKDOWN STRUCTURE

Illustrated on the facing page is the work breakdown for the SPS as selected by NASA. This work breakdown structure was used for the system descriptions to be prepared at the conclusion of the Phase I contract activity.

New Solar Power Satellite Program WBS

- 1.0 SOLAR POWER SATELLITE PROGRAM
  - 1.1 SATELLITE
    - 1.1.1 ENERGY CONVERSION
      - .1 STRUCTURE
      - .2 CONCENTRATORS
      - .3 SOLAR BLANKET
      - .4 POWER DISTR.
      - .5 THERMAL CONTROL
      - .6 MAINTENANCE
    - 1.1.2 POWER TRANSMISSION
      - .1 STRUCTURE
      - .2 TRANSMITTER SUBARRAYS
      - .3 POWER DISTR.
      - .4 THERMAL CONTROL
      - .5 CONTROL
      - .6 MAINTENANCE
      - .7 MECHANICAL POINTING [1]
    - 1.1.3 INFORMATION MANAGEMENT AND CONTROL
    - 1.1.4 ATTITUDE CONTROL AND STATIONKEEPING
    - 1.1.5 COMMUNICATIONS
    - 1.1.6 INTERFACE (ENERGY CONV./POWER TRANSMISSIONS)
    - 1.1.7 SYSTEMS TEST
  - 1.2 SPACE CONSTRUCTION AND SUPPORT
    - 1.2.1 CONSTRUCTION FACILITIES
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
    - 1.2.2 LOGISTICS SUPPORT FACILITIES [2]
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
    - 1.2.3 O&M SUPPORT FACILITIES
      - .1 WORK SUPPORT
      - .2 CREW SUPPORT
      - .3 OPERATIONS
  - 1.3 TRANSPORTATION
    - 1.3.1 HLLV
    - 1.3.2 COTV
    - 1.3.3 PLV
    - 1.3.4 POTV
    - 1.3.5 PM
    - 1.3.6 IOTV
    - 1.3.7 GROUND SUPPORT FACILITIES
  - 1.4 GROUND RECEIVING STATION
    - 1.4.1 SITE AND FACILITIES
    - 1.4.2 RECTENNA SUPPORT STRUCTURE
    - 1.4.3 POWER COLLECTION
    - 1.4.4 CONTROL
    - 1.4.5 GRID INTERFACE
    - 1.4.6 OPERATIONS
  - 1.5 MANAGEMENT AND INTEGRATION
    - 1.5.1 PROGRAM MANAGEMENT
    - 1.5.2 PROGRAM PLANNING AND CONTROL
    - 1.5.3 CONTRACTS ADMINISTRATION
    - 1.5.4 ENGINEERING MANAGEMENT
    - 1.5.5 MFG. MANAGEMENT
    - 1.5.6 SUPPORT MANAGEMENT
    - 1.5.7 QUALITY ASSURANCE MANAGEMENT
    - 1.5.8 CONFIGURATION MANAGEMENT
    - 1.5.9 DATA MANAGEMENT
    - 1.5.10 SYSTEMS ENGINEERING AND INTEGRATION

[2] BECOMES GEO BASE FOR THE LEO CONSTRUCTION OPTION

[1] ADDED

STUDY BASELINE CHANGES

The list of changes on the facing page are discussed on the following pages.

Study Baseline Changes

IMPLEMENTED

ITEM	REASON
STRUCTURE—ADDED MEMBERS	PROVIDE STABILITY AND REDUNDANCY
SOLAR ARRAY—ADDED SHUNTING DIODES	SHADOWING PROTECTION
POWER DISTRIBUTION—MULTIPLE BUSSES	LIMIT FAULT CURRENTS
POWER PROCESSING—LIQUID-COOLED TRANSFORMERS	LESS MASS & LONGER LIFE
RF GENERATION—LIQUID-COOLED KLYSTRONS	LESS MASS & AVOIDS ARCING IN LOSS-OF-COOLANT INCIDENT

RECOMMENDED

ITEM	REASON
5-GWe SPS	DOE/NASA BASELINE
PLATFORM (SINGLE-DECK) CONSTRUCTION BASE	SIMPLER & LESS COSTLY THAN "C-CLAMP"
PENTAHEDRAL TRUSS STRUCTURE	SIMPLER & LESS MASS
ADD 2.5 GWe SPS OPTION	MORE APPROPRIATE TO PROTOTYPE AND TO SOLID-STATE POWER AMPLIFIER

UPDATED EFFICIENCY AND SIZING

The efficiency chain was updated to reflect a slight improvement in intersubarray losses. This comes about because the earlier efficiency chain included a penalty for outages in the klystron power transmitter. These outages are also accounted for in the prediction of SPS plant factor in the maintenance and service analysis. This amounts to double bookeeping and the efficiency chain shown here reflects the beginning-of-operation capability. The solar blanket includes penalty factors for radiation degradation and other degradation factors such that the solar blanket is capable of supplying the required output over the life of the satellite with no servicing except annealing. One would then expect the SPS output to be recovered back to the beginning value at the conclusion of each maintenance and service period.

Updated Efficiency and Sizing

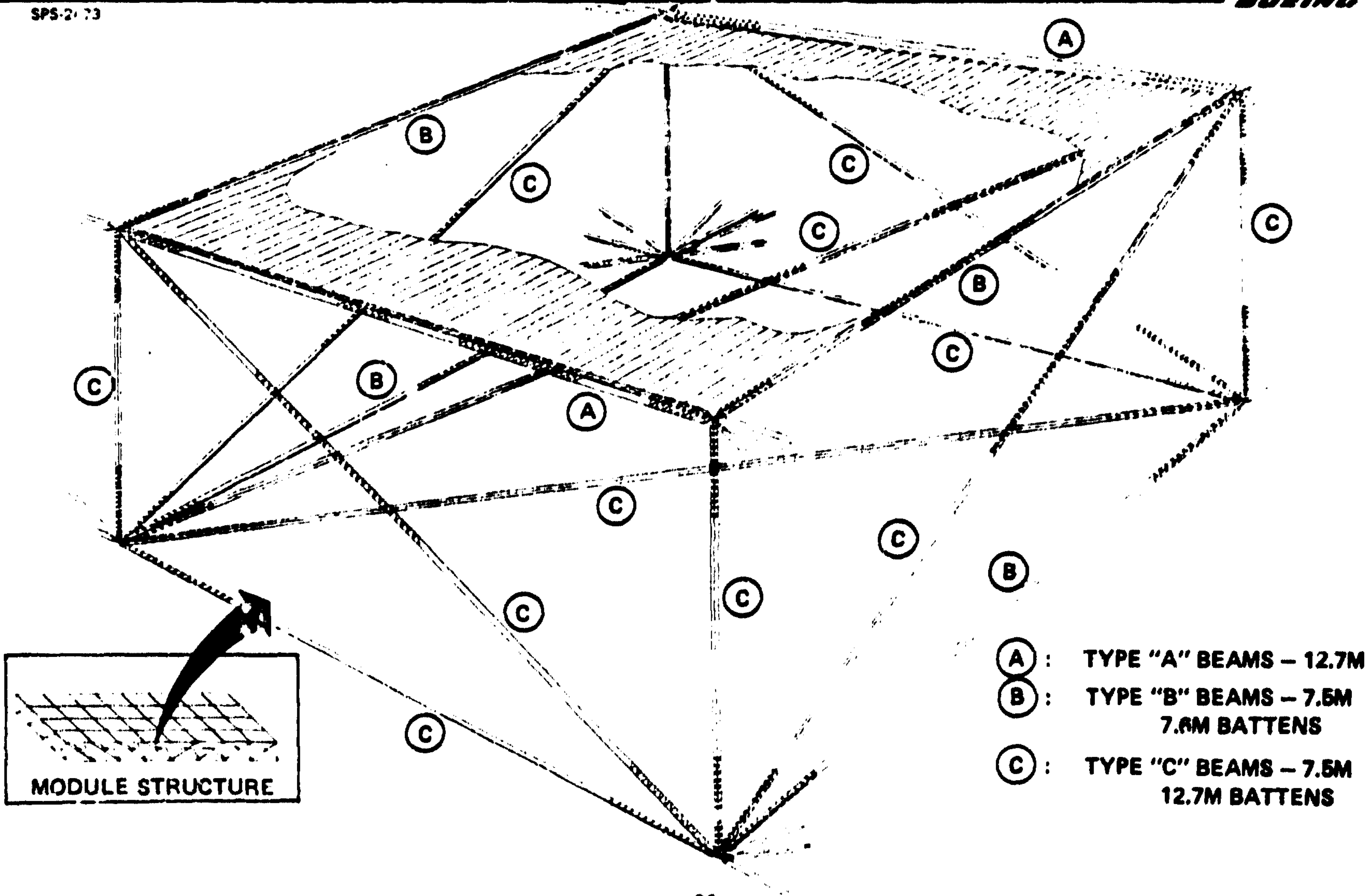
	EFFICIENCY	MEGAWATS PER LINK	
MAIN BUS I^2R	0.934	8,876	SOLAR ARRAY OUTPUT
ROTARY JOINT	1.0	8,290	
ANTENNA POWER DISTRIBUTION AND PROCESSING	0.97	8,290	TOTAL INPUT TO ANTENNA
DC-RF CONVERSION	0.85	8,041	
WAVEGUIDE I^2R	0.985	6,836	TOTAL RF POWER
IDEAL BEAM	0.965	6,733	TOTAL RADIATED POWER
INTER-SUBARRAY LOSSES	0.976	6,497	
INTRA-SUBARRAY LOSSES	0.981	6,341	
ATMOSPHERE LOSSES	0.98	6,221	
INTERCEPT EFFICIENCY	0.95	6,097	
RECTENNA RF-DC	0.89	5,792	INCIDENT ON RECTENNA
GRID INTERFACING	0.97	5,155	
	0.563	5,000	NET TO GRID

SOLAR INPUT:	1,353 W/m^2
SOLAR-CELL CONVERSION EFFICIENCY (0.173)	234.1
BLANKET FACTORS (0.9453)	221.3
THERMAL DEGRADATION (0.954)	211.1
ORIENTATION LOSS (0.919)	194.0
APHELION INTENSITY (0.9675)	187.7
NONANNEALABLE RADIATION DEGRATION (0.97)	182.1
ORBIT TRANSFER COMPENSATION (0.99)	180.2
REGULATION, AUXILIARY POWER, AND ANNEALING (0.983)	177.2
EOL BLANKET OUTPUT:	177.2 W/m^2
TOTAL SOLAR-CELL AREA:	50.1 km^2
SOLAR ARRAY OUTPUT:	8,876 MW

SOLAR POWER SATELLITE STRUCTURAL BAY CONFIGURATION

The structural bay design was updated based on new loads analysis to reflect the load requirements for self-power orbit transfer and solar blanket stretching loads. For the case of geosynchronous orbit construction, the type B beams shown on the chart can be changed to type C since orbit transfer loads will not be a consideration.

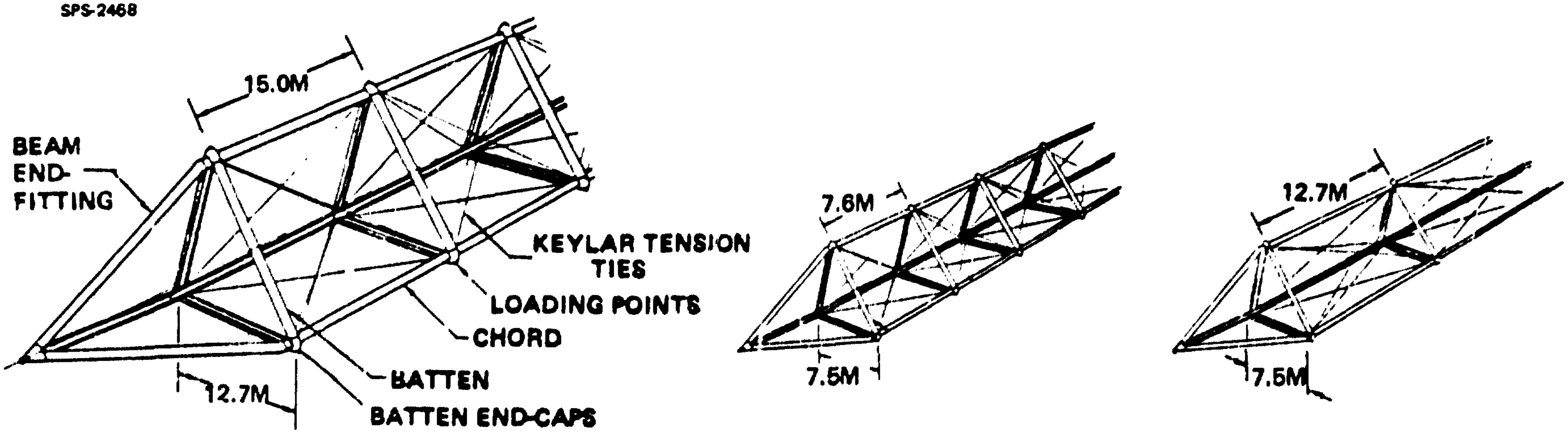
Solar Power Satellite Structural Bay Configuration



SOLAR POWER SATELLITE STRUCTURAL UPDATE BEAM CONFIGURATIONS

The three types of beams illustrated on the previous chart are characterized in additional detail here.

Solar Power Satellite Structural Update Beam Configurations



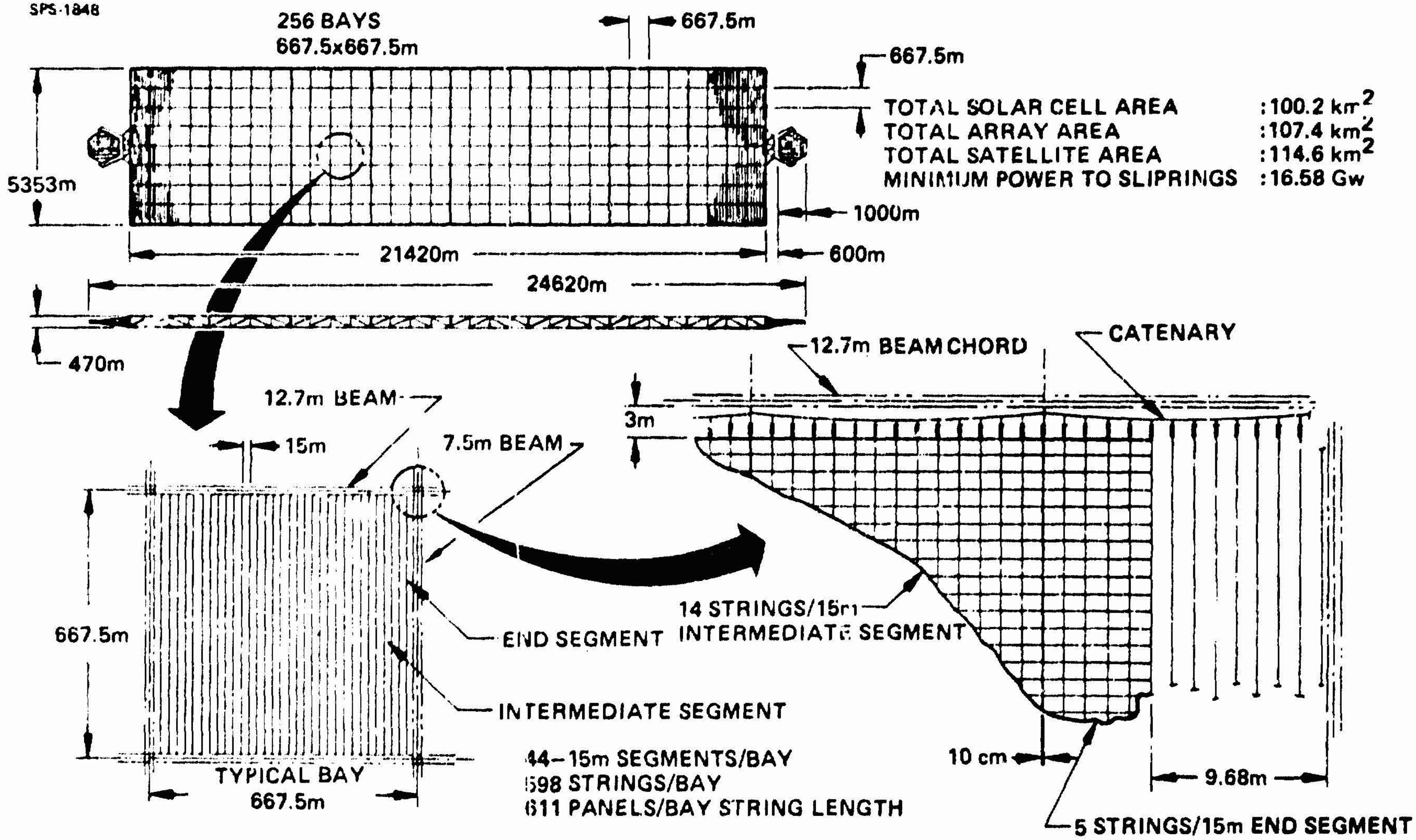
ITEM	TYPE A UPPER SURFACE LONGITUDINAL BEAM	TYPE B UPPER AND LOWER SURFACE LATERAL BEAM	TYPE C BEAM USED IN ALL OTHER LOCATIONS
SECTION	CLOSED	OPEN	OPEN
REF. SIDE LENGTH	38 CM	38CM	38CM
MAT'L THICKNESS	0.86 MM	0.71 MM	0.71 MM
EI_X	3.39 E8 N/CM^2	1.80 E8 N/CM^2	1.80 E8 N/CM^2
BEAM WIDTH	12.7M	7.5M	7.5M
BATTEN SPACING	15.0M	7.6M	12.7M
CRITICAL LOAD	17480N (CRIP. CHORD)	19000 N (BUCK. BEAM)	7090 N(BUCK BEAM)
MASS/LENGTH	7.48 KG/M	5.12 KG/M	4.11 KG/M

REFERENCE PHOTOVOLTAIC SYSTEM DESCRIPTION

Illustrated here is the update of the photovoltaic system for the 10,000 megawatt study baseline SPS. The solar array has been resized based on the efficiency change analysis and update of systems performance.

Reference Photovoltaic System Description

SPS-1848



TOTAL SOLAR CELL AREA	:100.2 km^2
TOTAL ARRAY AREA	:107.4 km^2
TOTAL SATELLITE AREA	:114.6 km^2
MINIMUM POWER TO SLIPRINGS	:16.58 Gw

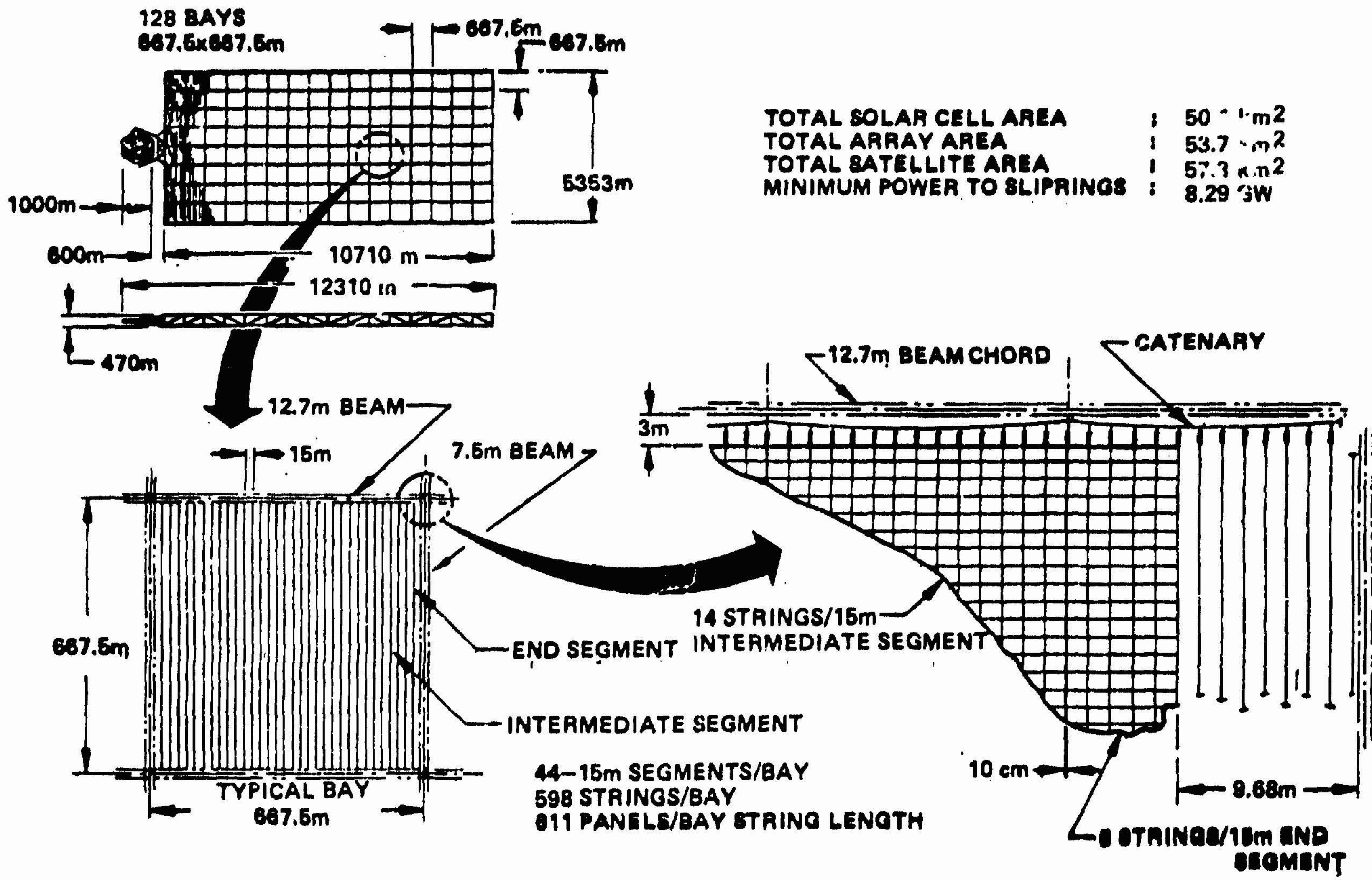
5,000 MEGAWATT REFERENCE PHOTOVOLTAIC REFERENCE SYSTEM DESCRIPTION

This figure illustrates the system for the NASA baseline reference case of 5,000 megawatts and silicon solar blanket.

D180-25037-5

5000 Megawatt Reference Photovoltaic System Description

SPS-2470



TOTAL SOLAR CELL AREA	:	50 [illegible] m2
TOTAL ARRAY AREA	:	53.7 [illegible]m2
TOTAL SATELLITE AREA	:	57.3 [illegible]m2
MINIMUM POWER TO SLIPRINGS	:	8.29 [illegible]W

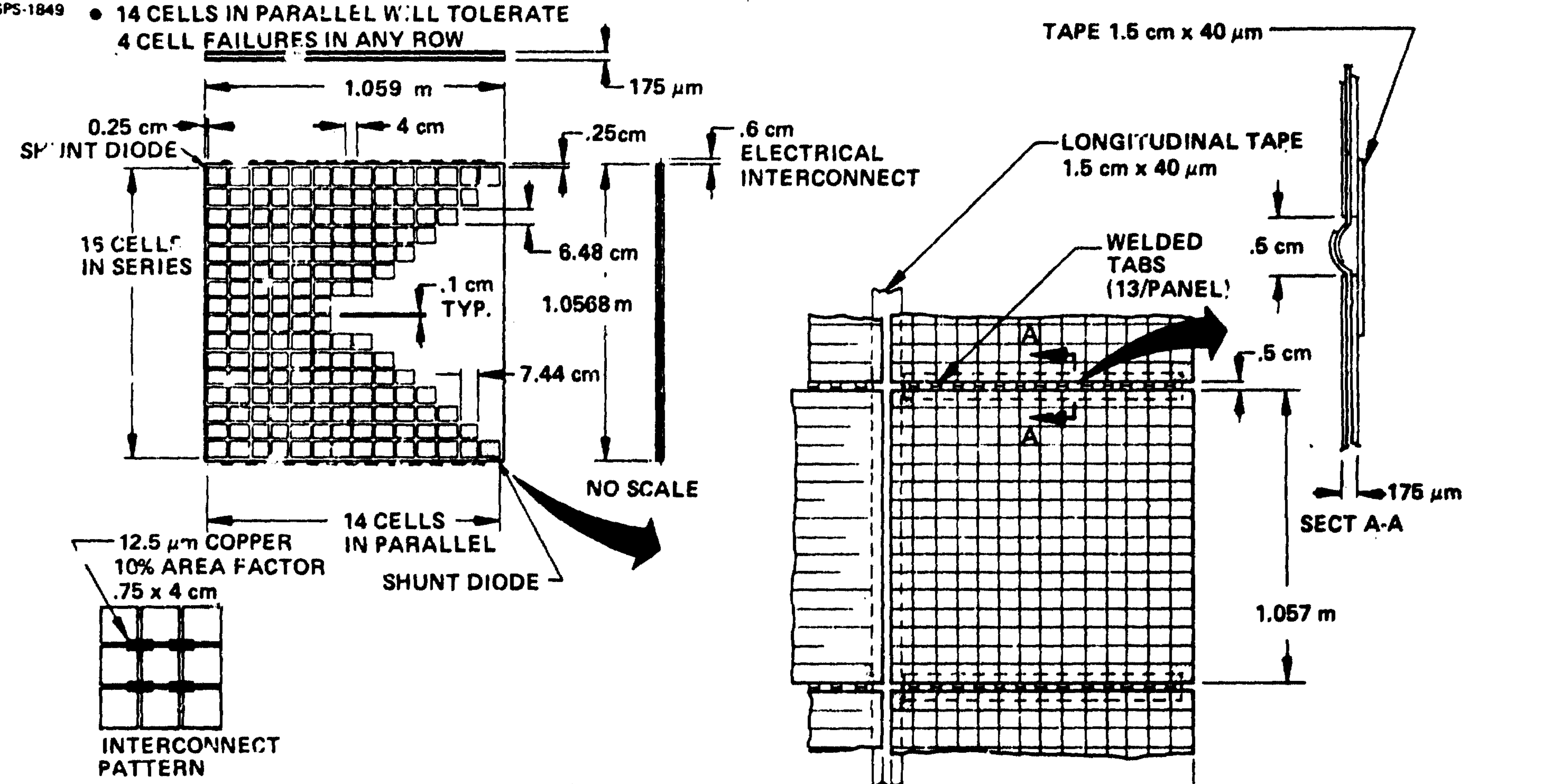
REFERENCE PHOTOVOLTAIC SYSTEM DESCRIPTION

The solar blanket design has been updated to include shunting diodes required to provide shadowing protection. The shadowing protection is provided at the blanket panel level. In the event of shadowing or some other fault within the blanket, each panel can be bypassed by the shunting diodes to prevent reverse breakdown failure.

Reference Photovoltaic System Description

SPS-1849

- 14 CELLS IN PARALLEL WILL TOLERATE 4 CELL FAILURES IN ANY ROW



#CELLS/PANEL	:222
PANELS/BAY	:365,378
PANELS/SATELLITE	:9,353,678

GIMBALLED SCANNING LASER CHARACTERISTICS UPDATE

Based on current annealing test data the laser annealing system has been updated to reflect a significantly lower power requirement. Time to anneal the array was held constant at the 147 days value.

Gimbaled Scanning Laser Characteristics Update

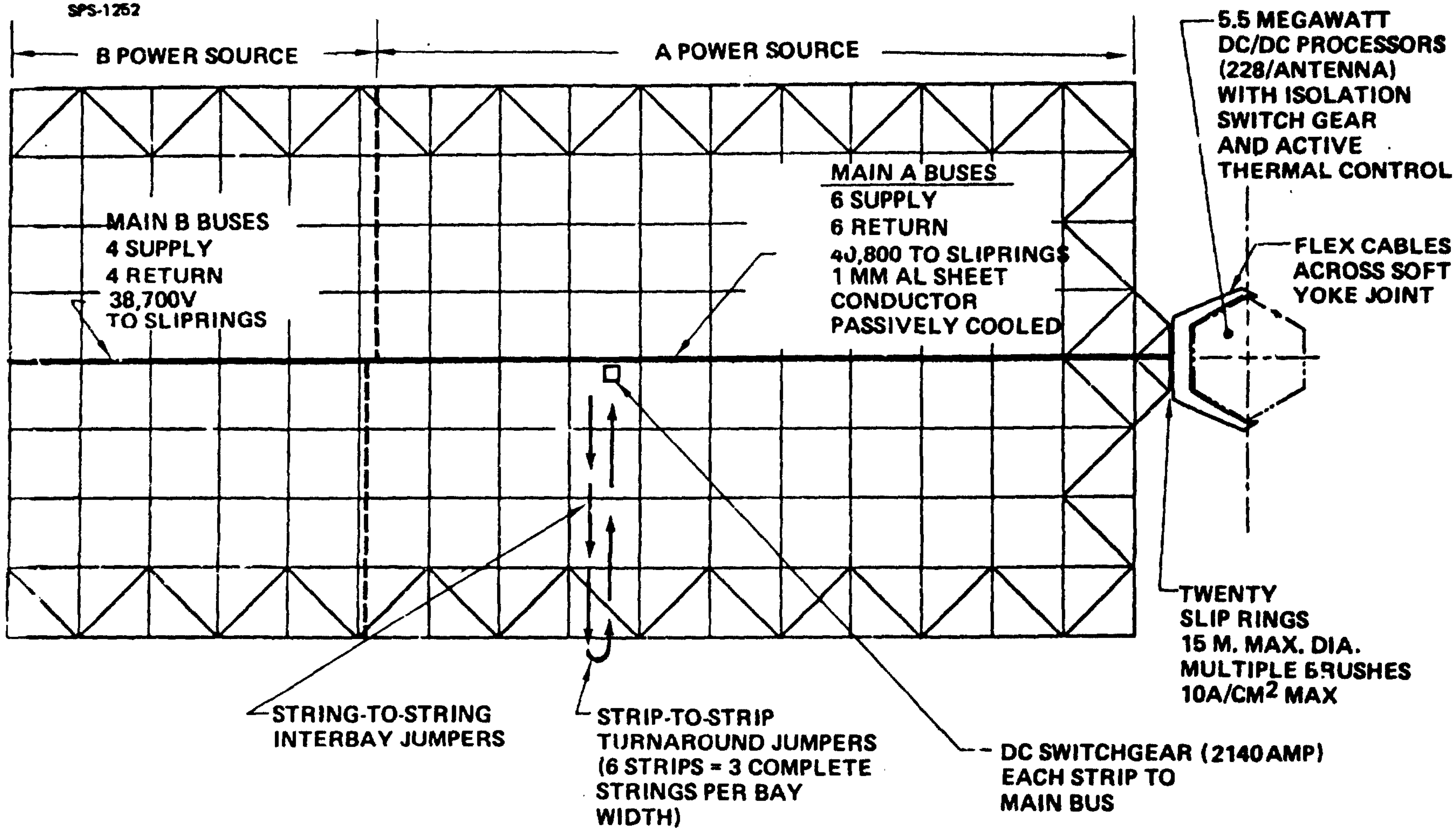
• ANNEALING ENERGY DENSITY:	16 W-sec/cm^2
• POWER DENSITY:	8 W/cm^2
• T_{MAX} (ACTIVE REGION):	550^{o}C
• LASERS/GIMBAL:	8
• SCANNING SPOT SIZE:	500 cm^2 (44.0 x 11.4 cm)
• SPOT SWEEP RATE:	5.7 cm/s
• POWER REQUIRED/LASER GIMBAL:	26.7kW
• POWER REQUIRED/GANTRY:	1.17 MW
• NUMBER OF GANTRIES/SATELLITE:	8 (1/SATELLITE MODULE)
• TOTAL ANNEALING POWER REQUIREMENT:	9.4 MW
• TIME REQUIRED TO ANNEAL ARRAY:	147 DAYS

MULTIPLE BUS SPS POWER DISTRIBUTION

Failure effects analyses indicated that the previous three-bus configuration could cause very large fault currents in the event of certain types of arcs. Because of this problem, the bus configuration was changed to reflect the use of 10 buses independent of one another. Major characteristics of the busing system are indicated on the facing page.

Multiple Bus SPS Power Distribution

SPS-1252



SLIPRING ASSEMBLY FOR MULTIPLE BUS POWER DISTRIBUTION SYSTEM

Selection of 10 independent buses required a redesign of the slipring assembly to provide a total of 20 rings. The major features of the design are shown on the facing page.

SPS-2552

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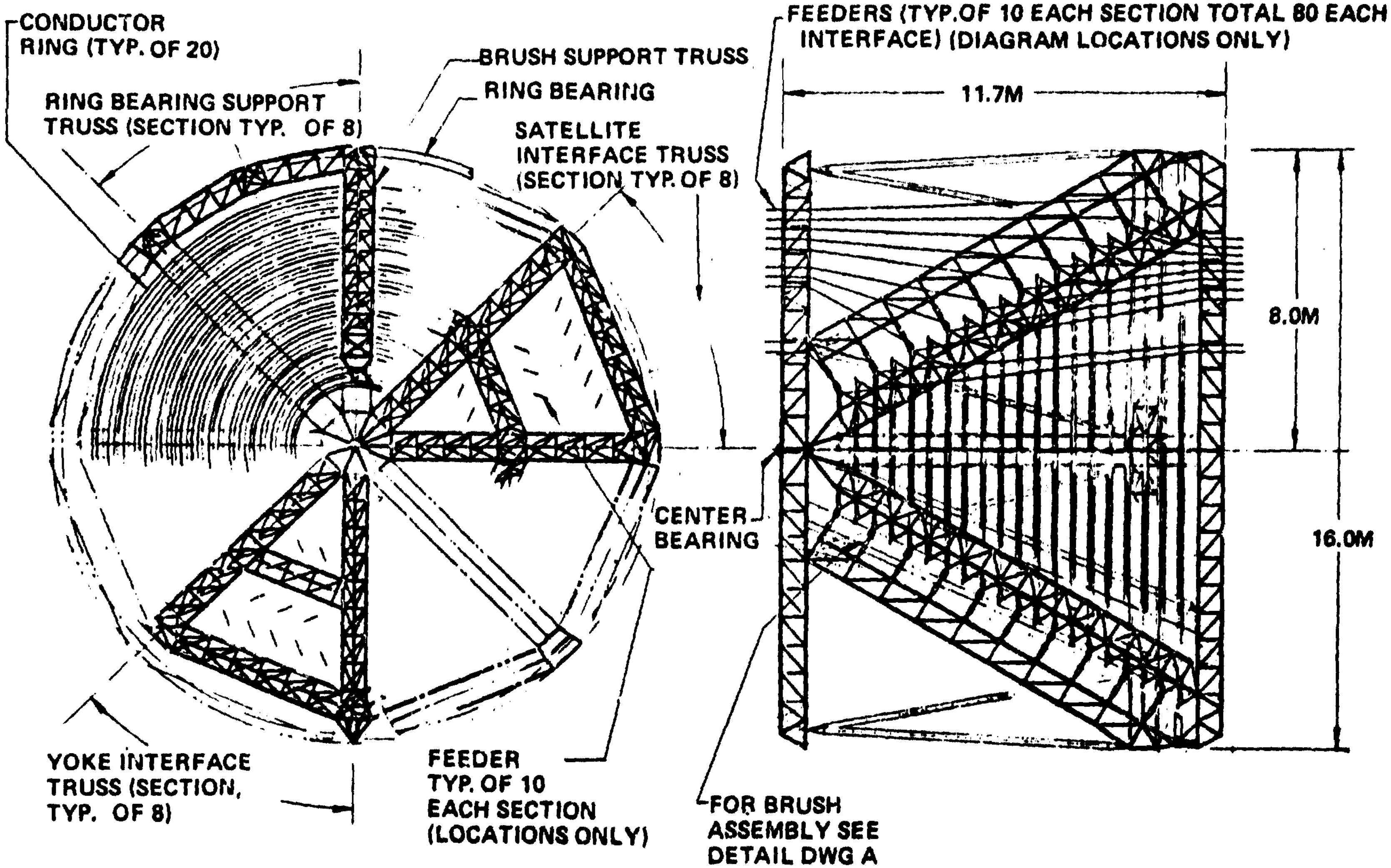
Slip Ring Assembly for Multiple Bus Power Distribution System

BOEING



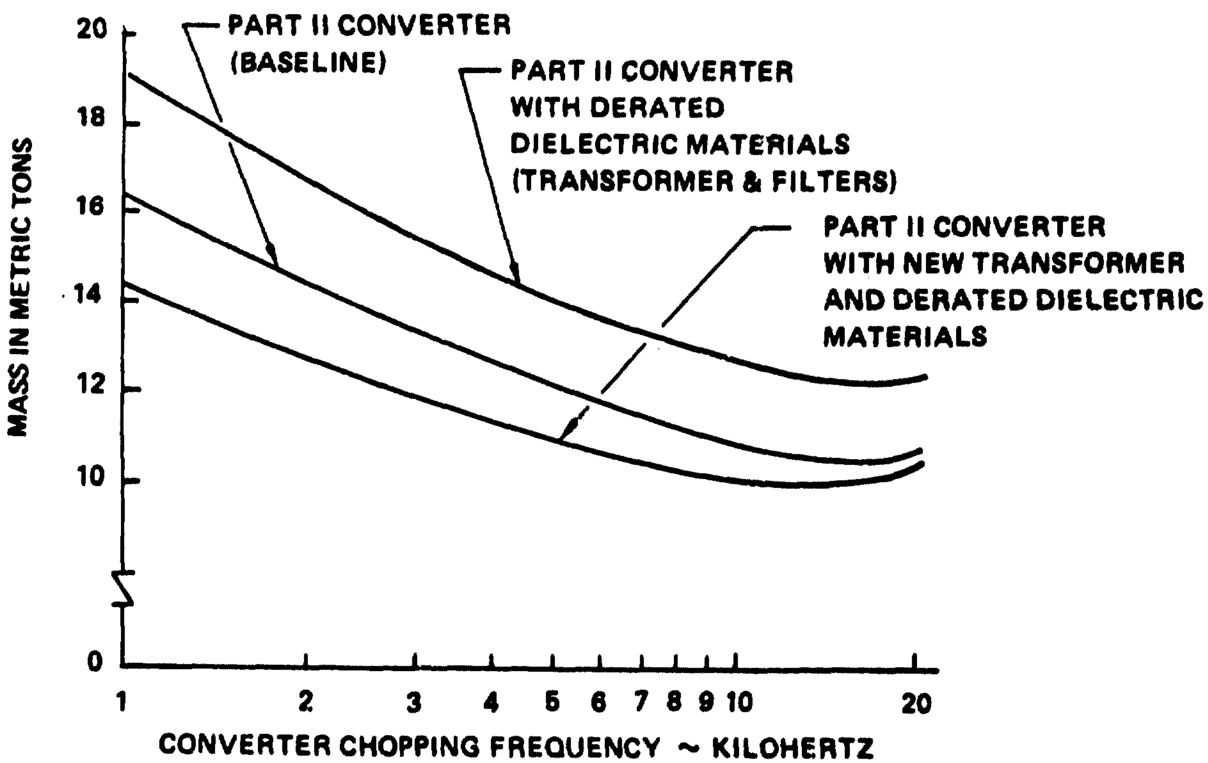
DC/DC CONVERTER SWITCHING FREQUENCY SELECTION

Analyses of the lifetime expectancy for the earlier DC-to-DC converters indicated a significant problem with dielectric material life. If that converter were derated to reflect a 20-year life an increase in mass would be expected as illustrated. However, a new transformer technology using liquid-cooled transformers provides long life with less mass than the earlier system. Shown here is the optimization of converter chopping frequency.

DC/DC Converter Switching Frequency Selection

SPS-2513

- MASS = CONVERTER MASS + THERMAL CONTROL MASS + ARRAY MASS (REQUIRED TO MAKE UP FOR CONVERTER LOSSES)



ANTENNA STRUCTURE OPTIONS

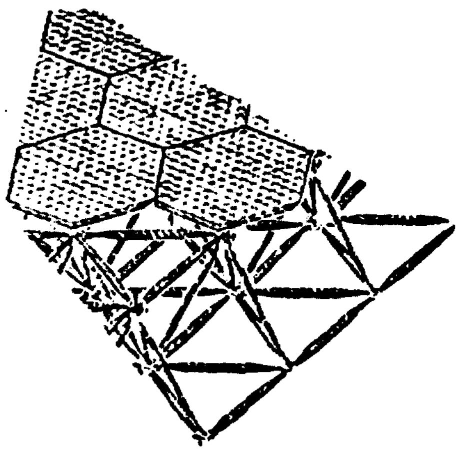
Early investigations of the SPS microwave power transmission systems antenna structure developed the tetrahedral truss primary and secondry structure concept. This system represents a maximum of structural efficiency for such an antenna. However, it constrains the subarrays to a non-square system and presented certain difficulties with respect to maintenance access.

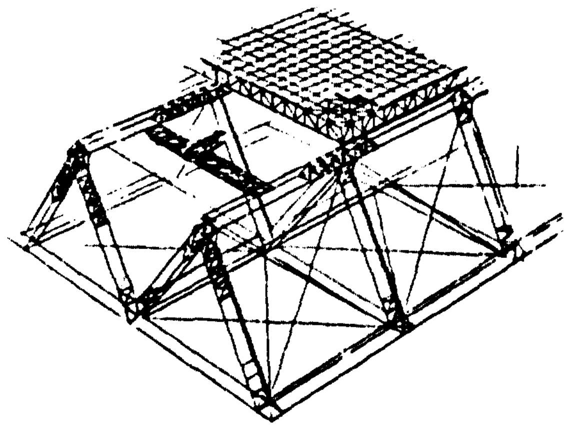
The center illustration in the facing page represents the antenna structure as visualized by the maintenance engineer. It provides easy access to subarray repair or replacement and allows square subarrays but structurally is not very efficient and employs tension members. The use of tension members results in dubious dynamic qualities for the structure. Further, the secondary structure is required to provide stability of the primary structure. Analysis of this combination indicated a relatively poor stiffness efficiency.

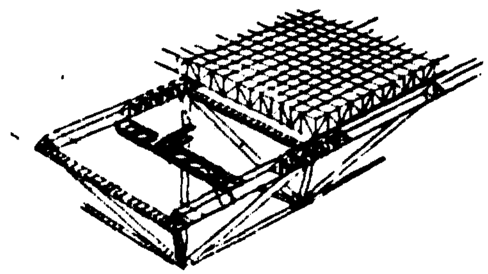
The pentahedral truss appears to offer a good compromise. It maintains good access with good efficiency, eliminates tension members and allows square subarrays.

At the beginning of Phase II, the solar array and MPTS structures will be updated to reflect the pentahedral truss configuration.

Antenna Structure Options







TETRAHEDRAL TRUSS

- MAXIMUM EFFICIENCY
- NO TENSION MEMBERS
- NON-SQUARE SUBARRAYS
- MAINTENANCE ACCESS DIFFICULT

A-FRAME

- GOOD ACCESS
- SQUARE SUBARRAYS
- POOR EFFICIENCY
- USES TENSION MEMBERS
- SECONDARY STRUCTURE IS PART OF PRIMARY STRUCTURE

PENTAHEDRAL TRUSS

- GOOD ACCESS
- GOOD EFFICIENCY
- NO TENSION MEMBERS
- SQUARE SUBARRAYS

KLYSTRON MODULE THERMAL CONTROL SYSTEM CHARACTERISTICS

Failure analyses also indicated a problem with the heat-pipe-cooled klystron. The difficulty was that the 500°C segment would utilize a mercury vapor heat pipe. In the event of a meteoroid puncture or other leak, the liquid metal would be released into the high voltage environment of the transmitter system and lead to arcing and damage. Plating of liquid metals on insulators might lead to a permanent damage situation that would require repair and replacement. Vought Corporation examined a circulating fluid cooling option and found that a mass reduction was possible and that fluids could be selected that would minimize risk of arcing. Their analysis indicates that a circulating fluid system can be made as reliable as the heat pipe system and certainly more reliable than the expected lifetime of the klystron themselves. The facing page shows principal features of the circulating fluid system for the klystron cooling circuit.

Klystron Module Thermal Control System Characteristics

BOEING

VOUGHT CORPORATION

	500°C	300°C
MATERIAL	COPPER	COPPER
FLUID	STEAM @ 20 ATM	DOWTHERM–A
INLET TEMP	477°C	277°C
OUTLET TEMP	413°C	260°C
LENGTH X WIDTH	0.57m x 1.61m	1.04m x 1.61m
TUBE SPACING	3.7 cm	2.84 cm
TUBE DIAMETER	5.6 mm	1.27 mm
TUBE THICKNESS	0.886 mm	0.71 mm
FIN THICKNESS	0.163 mm	0.066 mm
EMISSIVITY	0.8	0.8
ABSORTIVITY	0.3	0.3
TSINK	36.3°C	36.6°C
PUMP EFFY.	0.3	0.3
FIN EFFECTIVENESS	0.894	0.920
AREA	0.91 m^2	1.67 m^2
MASS/MODULE	7.95 kg	5.13 kg

CURRENT MASS/MODULE – 13.18 kg
PART III MASS/MODULE – 18.88 kg

COMPARISON OF LOSSES FOR METAL AND COMPOSITE WAVEGUIDE

Included in the analysis of aluminum structural options was the analysis of use of aluminum for the waveguides in the transmitting antenna. Aluminum has a high coefficient of thermal expansion compared to the graphite used in the earlier baseline. As a result, due to expected temperature changes, the aluminum waveguides will be significantly detuned resulting in power losses as tabulated on the facing page.

Comparison of Losses for Metal & Composite Waveguide

- AVERAGE STICK = 2.76 METERS
- $\Delta T = 55^{\circ}C$

	PERCENT POWER LOSS	
	ALUMINUM	COMPOSITE
STICK LENGTH	.67	.02
STICK WIDTH	.42	.12
CROSS GUIDE LENGTH	.17	.02
CROSS GUIDE WIDTH	.11	.03
	1.37%	.19%

ANTENNA WAVEGUIDE MATERIAL

Although the plated composite approach is probably a high risk based on today's knowledge because of potential breaks or delamination of the plating under thermal cycling or high RF power conditions, the cost advantages of a low-coefficient-of-thermal-expansion material are sufficient that development of a suitable such approach for waveguides should be identified as a priority development item for SPS.

Antenna Waveguide Material

- Low CTE-plated composite detuning loss is 0.2% compared to 1.3% for aluminum.
- Cost of 1% efficiency loss is $75 million per 5-GW SPS.
- Plated composite as high-risk, based on today's knowledge.
- Recommend using low-CTE characteristics for waveguide performance and mass; flag development of suitable material as high-priority research item.

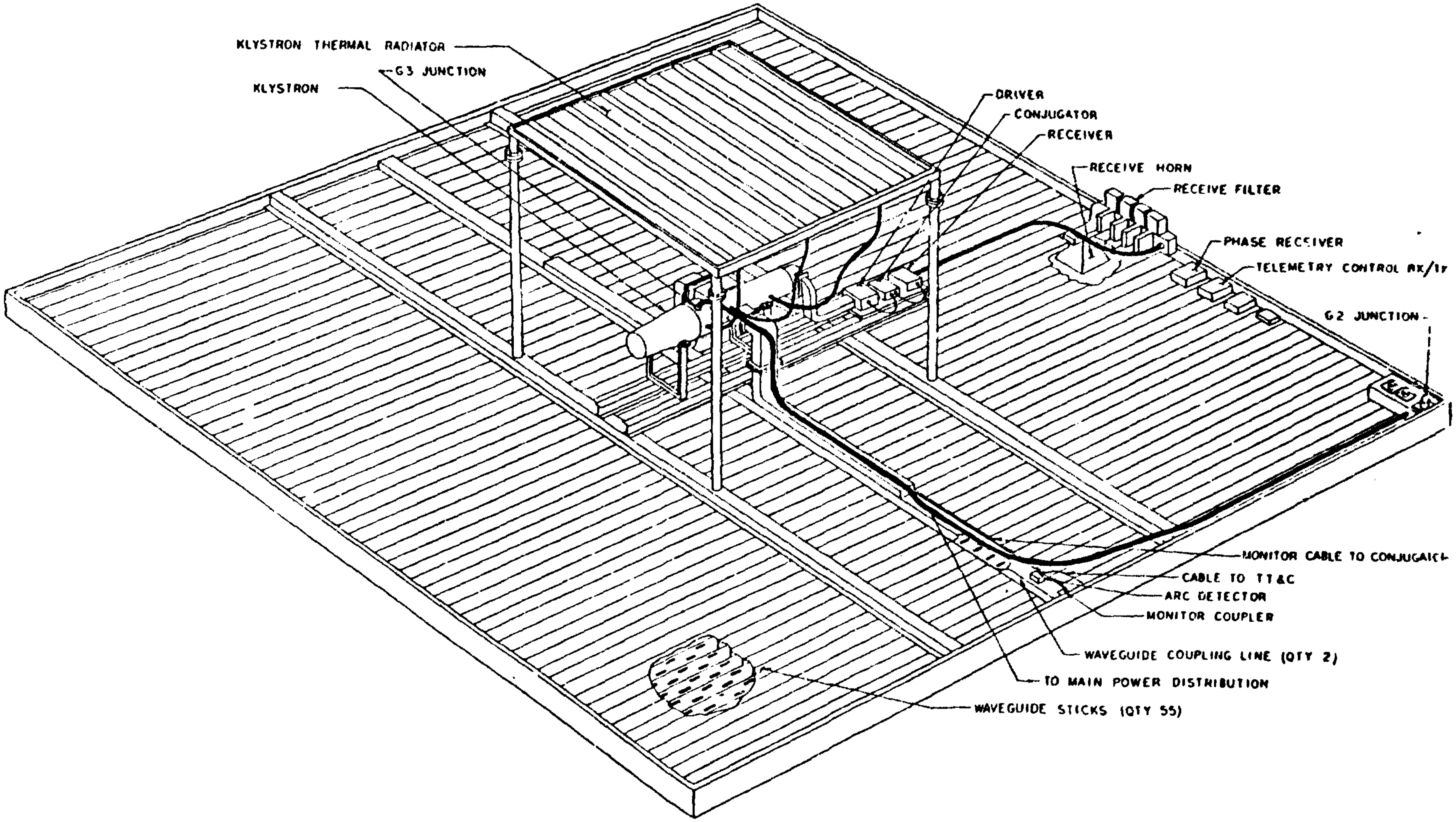
MECHANICAL LAYOUT OF A TYPICAL KLYSTRON MODULE IN THE OUTER RING OF THE SPACE ANTENNA

One of the General Electric subcontract tasks was to further define the mechanical layout of the klystrons including installation of phase control equipment. This chart illustrates the results of their layout effort. The appropriate redundancy levels are included in the layout.

GENERAL ELECTRIC

MECHANICAL LAYOUT OF A TYPICAL KLYSTRON MODULE IN THE OUTER RING OF THE SPACE ANTENNA

space division



REFERENCE MPTS MASS SUMMARY

This table presents a mass update for the microwave power transmission system including the mass reductions for the DC to DC converters and switchgear and klystron thermal control.

Reference MPTS Mass Summary

ITEM	MASS (MT)
PRIMARY STRUCTURE	52.5
SECONDARY STRUCTURE	197.5
ATTITUDE CONTROL	127.9
COMM/DATA	20.7
POWER DISTRIBUTION	2238.4
DC-DC CONV. & SWITCHGEAR – 1186.5	
THERMAL CONTROL – 222.1	
BUSSING – 397.9	
ENERGY STORAGE – 313.2	
SUPPORT – 118.7	
RF GENERATION AND DISTRIBUTION	9493.3
KLYSTRONS – 4874.5	
THERMAL CONTROL – 1612.6	
WAVEGUIDE ASSYS – 1795.6	
HARNESSES AND CONTROL CKTRY – 543.6	
SUBARRAY STRUCTURE – 667.0	
TOTAL MASS PER ANTENNA	12130
TOTAL MASS PER SATELLITE	24261

PHOTOVOLTAIC REFERENCE CONFIGURATION NOMINAL MASS SUMMARY

Changes in the system mass from the previous baseline description are summarized on this facing page. Reasons for the principal changes are given. The structural mass for primary structure represents siz for low Earth orbit construction. Geosynchronous orbit construction requires about 35% less structural mass.

Photovoltaic Reference Configuration
Nominal Mass Summary
Weight in Metric Tons

COMPONENT	PART III FINAL	CURRENT 10 GW	CURRENT 5 GW	REMARKS
1.0 SOLAR ENERGY COLLECTION SYSTEM	(55,602)	(58,308)	(29,191)	
1.1 PRIMARY STRUCTURE	7,155	9,729	4,864	CHANGE OF STRUCTURAL CONFIG. AND RESIZE
1.2 SECONDARY STRUCTURE	—	—	—	
1.3 MECHANICAL SYSTEMS	67	67	34	
1.4 MAINTENANCE STATION	—	—	—	
1.5 CONTROL	323	323	162	
1.6 INSTRUMENTATION/ COMMUNICATIONS	4	4	2	
1.7 SOLAR-CELL BLANKETS	45,773	45,632	22,916	ADD SHUNT DIODES AND RESIZE
1.8 SOLAR CONCENTRATORS	—	—	—	
1.9 POWER DISTRIBUTION	2,425	2,425	1,213	
2.0 MPTS	26,379	24,261	12,130	ACTIVE THERM. CONTR. DC/DC CONV. CHANGE
SUBTOTAL	81,998	82,589	41,321	
GROWTH	17,590	17,752	8,884	
TOTAL	99,713	100,321	50,205	

COST UPDATE

Revisions in the system have resulted in a revision to the cost estimates. Current values are compared to the value from the previous study all in 1977 dollars. Reasons for significant changes are given in the table. The pairs of values in the current columns represent values for low earth orbit construction and geosynchronous construction. No significant differences in amortized costs are seen. The information has been rearranged to reflect the current work breakdown structure and separation of capital cost factors from direct outlays.

Cost Update (Values are in Millions of 1977 Dollars for Comparison with Earlier Results)

SPS

SPS-2551

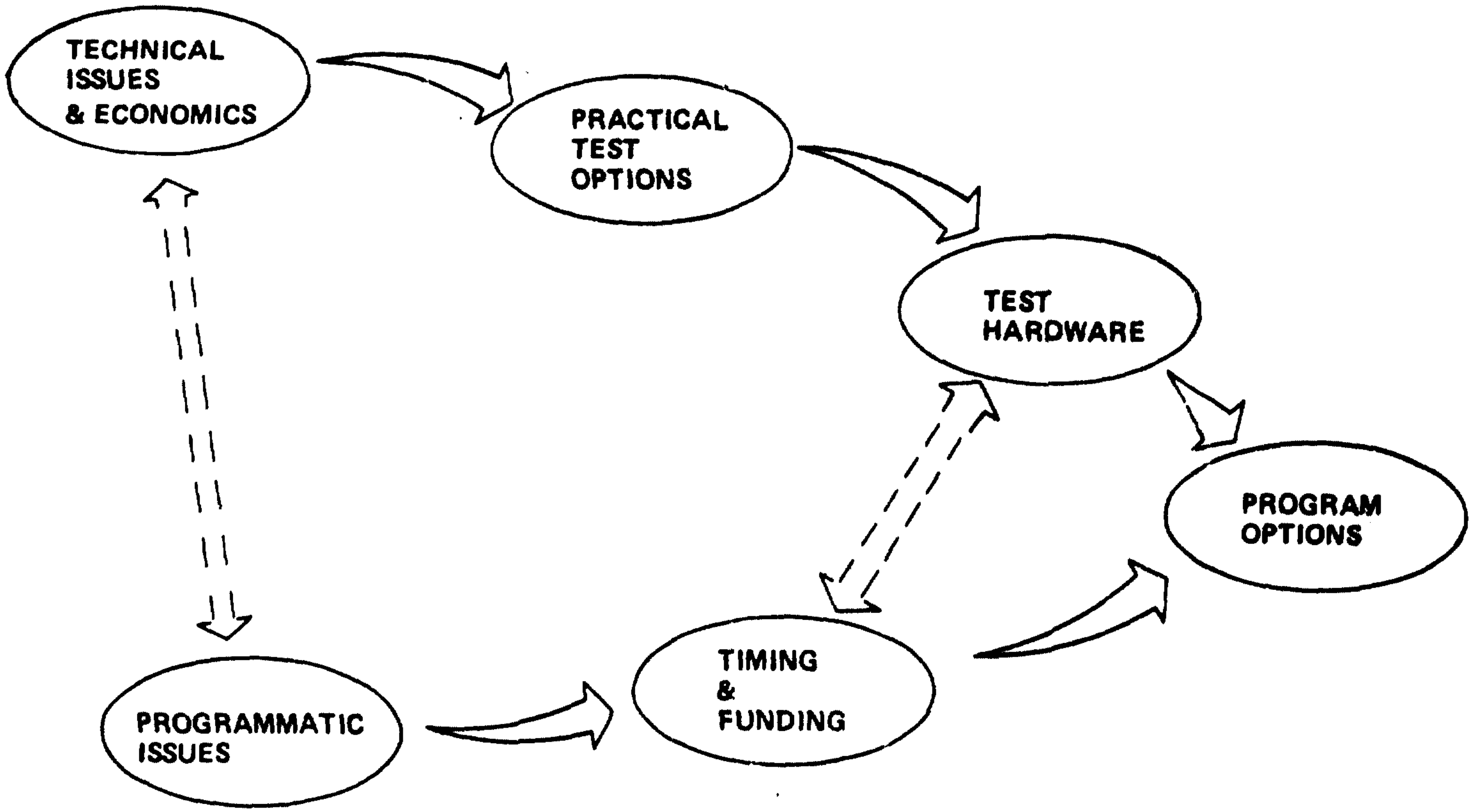
BOEING

ITEM		MARCH '78 VALUE	DEC '78 VALUE		SIGNIFICANT CHANGES
			10 GW	5 GW	
	CONSTRUCTION	(LEO)	(LEO/GEO)	(LEO/GEO)	
1.1	SATELLITE	7595	7740/7580	3871/3791	
1.1.1	ENERGY CONVERSION	4548	4621/4461	2311/2231	(1) SOLAR ARRAY RESIZED (2) STRUCTURE MASS GREATER
1.1.2	POWER TRANSMISSION	2454	2526	1263	(1) MASS REDUCTION (2) PHASE CONTROL REDUNDANCY
1.1.3	INFORMATION MGMT & CONTROL	84	84	42	
1.1.4	ATTITUDE CONTROL & STA. KEEP	287	287	144	
1.1.5	COMMUNICATIONS	222	222	111	
1.2	SPACE CONSTRUCTION AND SUPPORT	513	436	218	FEWER CREW
1.3	SPACE TRANSPORTATION	6387	5860/5315	2930/2658	ELECTRIC OTV/OTS RECOVERY
1.4	GROUND RECEIVING STATION	5868	5868	2934	
1.5	MANAGEMENT & INTEGRATION	842	842	421	
	TOTAL DIRECT OUTLAYS	21205	20746/20041	10374/10021	
	CAPITAL RECOVERY FOR SPACE TRANSPORTATION & CONSTRUCTION	595	1565/2290	783/1145	BETTER ACCOUNTING OF TRANSPORTATION INVESTMENT
	INTEREST DURING CONSTRUCTION	2082	1984/2094	992/1047	VARIATIONS IN TRANSPORTATION TRIP TIMES
	CONTINGENCY/GROWTH	3115	2489/2404	1245/1202	EARLIER FIGURE HAD GROWTH APPLIED TWICE TO CERTAIN TRANSPORTATION COSTS
	PROJECTED TOTAL CAPITAL COST	26,997	26784/26829	13394/13416	

PROGRAM OPTION DEFINITION

This bubble chart illustrates the overall approach to definition of SPS development program options. The two paths represent hardware and programmatic paths of analysis.

Program Option Definition



SPS DEVELOPMENT PHASES

Analyses of the programmatic structure of an SPS program have resulted in the multi-step approach illustrated on the facing page. Each step will provide knowledge and technical confidence leading to a program decision to initiate the next step. If the appropriate technical confidence from any step is not achieved, then the approach would be modified or possibly the program terminated if major difficulties were encountered.

SPS Development Phases

STEP	KNOWLEDGE GAINED	TECHNICAL CONFIDENCE	PROGRAM DECISION
EXPLORATORY STUDIES (COMPLETE)	SYSTEMS CONCEPT OPTIONS	THERE ARE NO FIRST ORDER TECHNICAL OR ECONOMIC SHOW-STOPPERS	PROCEED WITH SYSTEMS AND EVALUATION STUDIES
SYSTEMS STUDIES	CONCEPTUAL DESIGN CHARACTERIZATIONS OF SELECTED BASELINES; TECHNOLOGY PERFORMANCE OBJECTIVES	DESIGN APPROACHES EXIST THAT CAN PROBABLY ACHIEVE TECHNICAL AND ECONOMIC OBJECTIVES	INITIATE TECHNOLOGY RESEARCH AND CONTINUE EVALUATION STUDIES
TECHNOLOGY RESEARCH	ACTUAL TECHNOLOGY PERFORMANCE	TECHNOLOGY PERFORMANCE SUPPORTS SPS DESIGN APPROACHES	INITIATE ENGINEERING TECHNIQUES DEVELOPMENT
ENGINEERING TECHNIQUES DEVELOPMENT	SUBSYSTEMS AND SYSTEMS ENGINEERING PERFORMANCE; ADEQUATE BASIS FOR SPECIFICATIONS	SPS DESIGN APPROACHES VALIDATED; PREFERRED APPROACHES SELECTED	INITIATE FULL-SCALE DEVELOPMENT
FULL SCALE DEVELOPMENT	SPS "WORKS"	SPS CAN BE SUCCESSFULLY COMMERCIALIZED	ENTER COMMERCIAL PRODUCTION

SPS TECHNOLOGY RESEARCH PRIORITY OBJECTIVES

The purpose of the technology research phase is to develop confidence in the achievable technology performance in all the critical areas so that a much firmer assessment of SPS economics and environmental impact can be made. Listed on the facing page are the principal objectives of a technology research program required to obtain the necessary information.

SPS Technology Research—Priority Objectives

- DEVELOP SOLAR ARRAY TECHNOLOGIES INCLUDING ANNEALING
- DEVELOP SOLAR CELL/ARRAY PRODUCIBILITY APPROACHES
- DEVELOP SWITCHGEAR AND POWER PROCESSOR TECHNOLOGY
- DEFINE PLASMA EFFECTS OF HIGH-VOLTAGE SOLAR ARRAY OPERATION AND ELECTRIC PROPULSION OPERATION; DEVELOP SYSTEM DESIGN APPROACHES ACCORDINGLY
- DEVELOP PRACTICAL, LOW-COST MATERIALS TECHNOLOGIES FOR SPS APPLICATIONS
- DEVELOP INTEGRATED STRUCTURAL/ ELECTRICAL POWER DISTRIBUTION TECHNOLOGY FOR LONG-LIFE VACUUM OPERATION WITHOUT ELECTRICAL BREAKDOWN
- DEVELOP HIGH-EFFICIENCY, HIGH-SPECTRAL-PURITY RF GENERATION AND RADIATION TECHNIQUES
- DEVELOP PRECISION PHASE CONTROL TECHNOLOGIES
- DEFINE EFFECTS OF IONOSPHERE AND SPACE PLASMAS ON POWER TRANSMISSION AND PHASE CONTROL; DEVELOP DESIGN APPROACHES ACCORDINGLY
- DEVELOP HIGH-EFFICIENCY POWER RECEPTION AND COLLECTION TECHNIQUES
- DEVELOP SPACE FABRICATION AND ASSEMBLY TECHNOLOGIES

ENGINEERING TECHNIQUES DEVELOPMENT
LONG LEAD ITEMS

Many of the technology requirements for SPS are of an engineering nature, where the performance of the technology can be reasonably well forecast, but significant developments are still required in order to be able to construct SPS's at some meaningful rate. These areas are termed engineering techniques developments. Certain of these may present calendar time problems and are listed on the facing page.

Engineering Techniques Development – Long-Lead Items

- DEVELOPMENT TEST ARTICLE
- SPACE VEHICLE ENGINES: BOOSTER; ORBIT TRANSFER CHEMICAL & ELECTRIC; SSME IMPROVEMENTS
- THERMAL SYSTEMS: VEHICLE TPS; THERMAL COATINGS; ACTIVE THERMAL CONTROL
- SOLAR ARRAY PRODUCTION SYSTEMS
- RF AMPLIFIER & SUBARRAY PRODUCTION SYSTEMS
- SPACE CONSTRUCTION: CREW HABITATS & CREW SUPPORT SYSTEMS; CONSTRUCTION EQUIPMENT; BASE LOGISTICS SYSTEMS

SPS DEVELOPMENT PROGRAM STRUCTURE

Many types of activities are required to get from today's state of knowledge to a commercially acceptable SPS. The top three bars represent the technology research activities.

The development test article must be initiated relatively early in order to support design of a prototype SPS. During the prototype design period, development of the production technology and production capability will continue. Space operations systems including launch vehicles and a prototype production space construction base must be developed in order to support the prototype program. Depending on the size of the prototype, it may be possible to have a late start on the heavy lift launch vehicle to spread out the space vehicle systems development costs. Shown on the lower righthand portion of the schedule chart is the initiation of a commercial production program.

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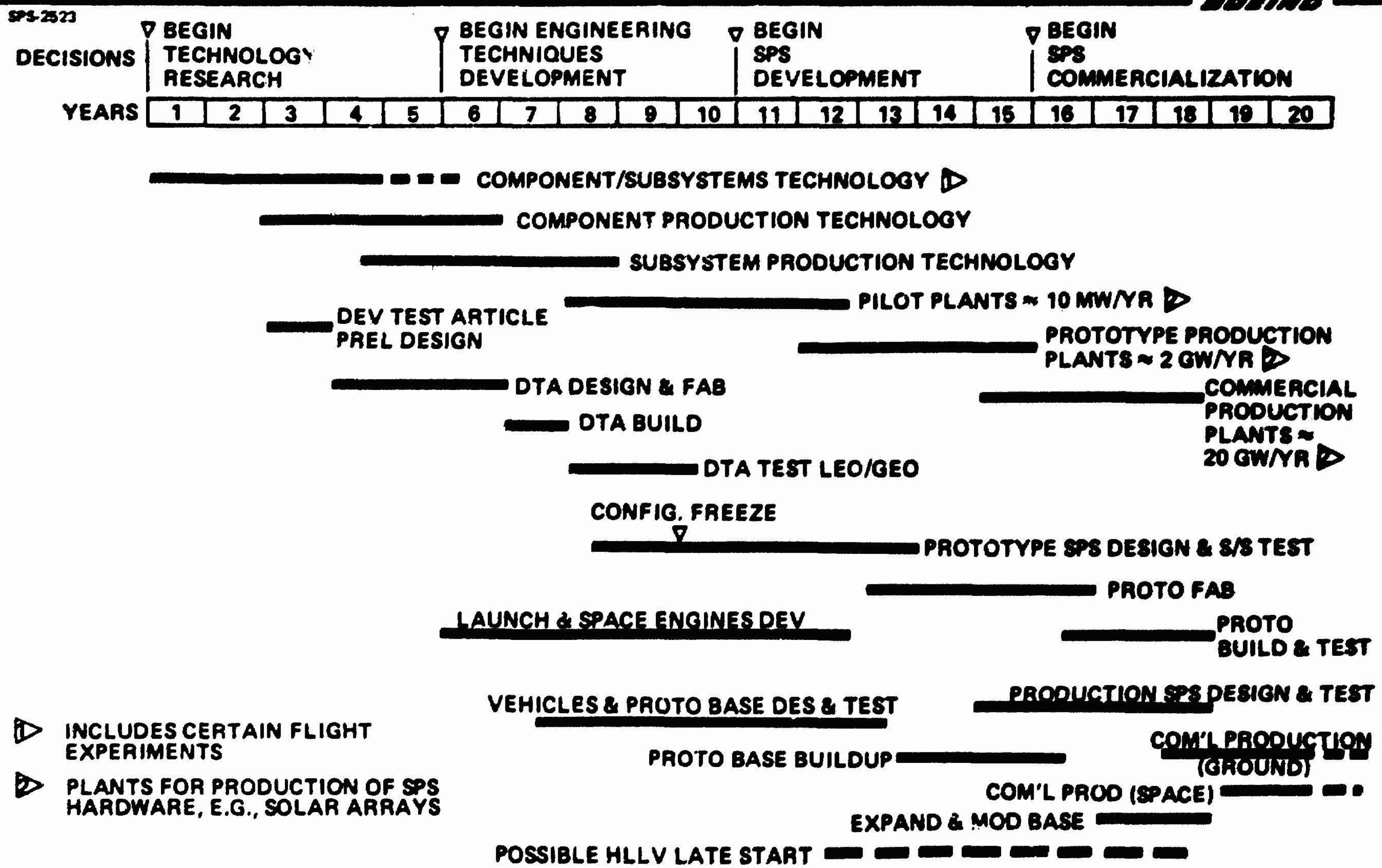
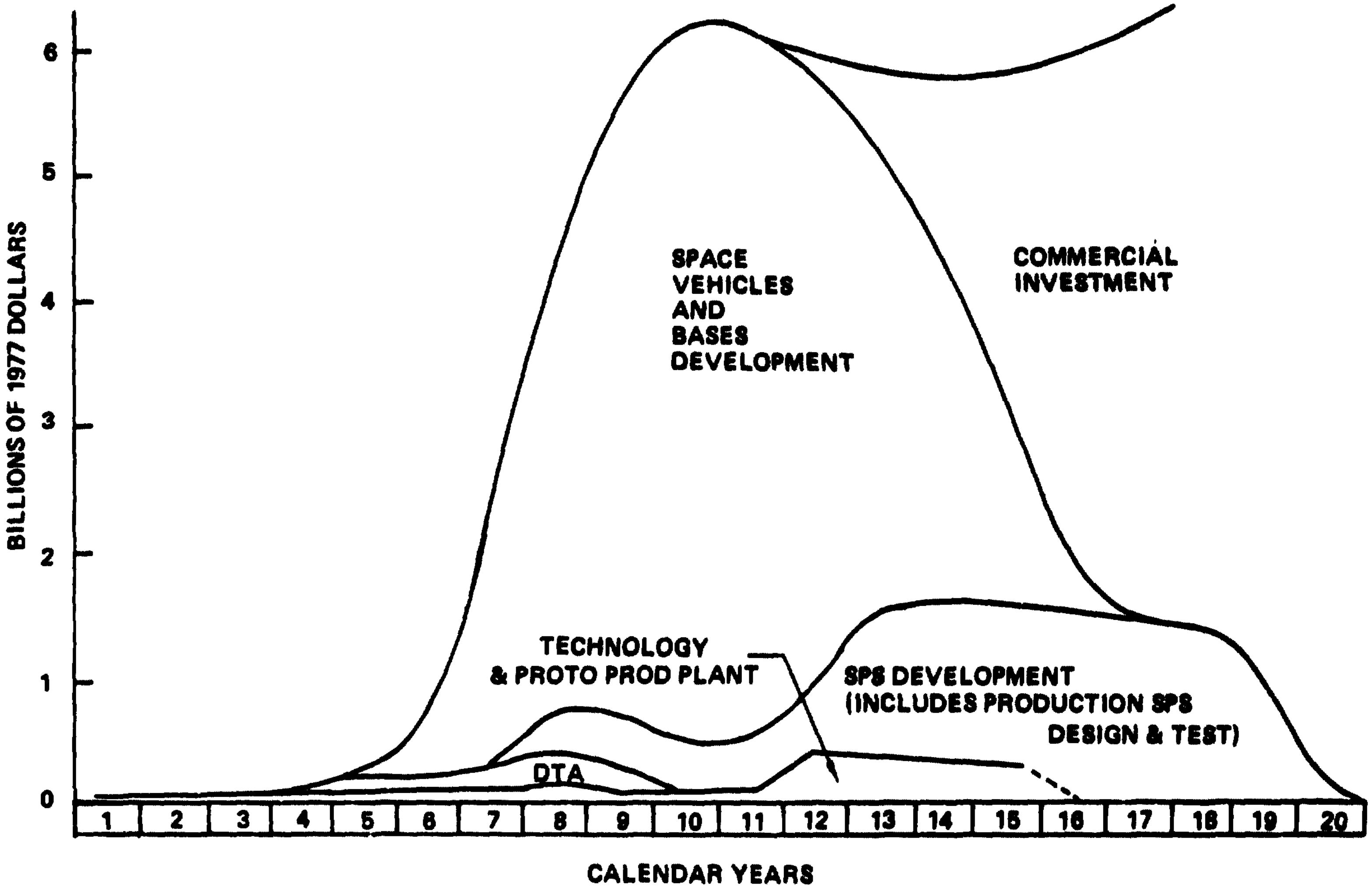
SPS Development Program Structure (Early Commercialization)



GENERAL NATURE OF NONRECURRING SPS FUNDING

The principal activities shown on the schedule chart are represented here in a preliminary estimate of funding requirements. It is clear that the funding requirements occur when beginning the development of space vehicles and space construction bases.

General Nature of Non-Recurring SPS Funding



COST DEFERRAL OPTIONS

There are a number of options available to smooth or reduce the funding peak shown on the previous chart. Some of the principal ones are tabulated here. The cost deferrals have consequences that may not be particularly desirable, but do offer the potential of reducing funding peaks.

Cost Deferral Options

ITEM	AMOUNT DEFERRED (ROM)	COST OF DEFERRAL	CONSEQUENCE OF DEFERRAL
DEFER MAIN COMMERCIALIZATION BUILDUP UNTIL PROTOTYPE TESTS COMPLETE	\$30-\$40B; 5 YEARS; SOME IS COMMERCIAL	\$3 TO \$5B	PRODUCTION SPS PROGRAM DELAYED 5 YEARS
DEFER HLLV TO SUPPORT ONLY COMMERCIAL PROGRAM; DO PROTOTYPE WITH SHUTTLE DERIVATIVE	\$20B; 5 YEARS	\$2 TO \$5B; DEPENDS ON PROTOTYPE SIZE	HLLV COST CHARACTERISTICS NOT DEMONSTRATED WHEN COMMERCIAL INVESTMENTS REQUIRED
INITIALLY COMMERCIALIZE TO 5 GW/YR RATE	\$5-\$10B; UNTIL HIGHER RATE IMPLE-MENTED	UNIT COST SOMEWHAT HIGHER AT REDUCED PRODUCTION	SLOWER SPS CAPACITY BUILDUP

DEVELOPMENT PROGRAM ANALYSIS CONCLUSIONS

The development test article is needed early to provide design data for the SPS prototype design. It should be of the size to permit early funding; 1 megawatt or less. It is possible that the development test article will be constrained by photovoltaic's production capability, but it does not appear important that the development test article represent a final solar blanket configuration.

We have identified the need for an SPS prototype, but there is still a major uncertainty in how large the prototype should be. It seems clear that whatever size prototype is selected, it should provide efficient power transfer. If it is a low power system it will still have a large transmitter aperture.

The major funding requirements arise from development from space bases and heavy lift launch vehicles. Some cost deferral options exist to reduce the peak funding to a degree, but their benefits in an economic sense are quite dubious unless it is expected that the completion of the prototype would result in a decision not to proceed with commercialization of SPS's. If commercialization proceeds, then the economic cost of these deferrals tends to exceed their value.

Development Program Analysis Conclusions

- DEVELOPMENT TEST ARTICLE NEEDED EARLY–
  SHOULD BE SCALED TO PERMIT EARLY FUNDING
  (1 MEGAWATT OR LESS–MAY BE CONSTRAINED BY PHOTOVOLTAICS PRODUCTION CAPABILITY)

- PROTOTYPE SIZE PREFERENCE UNCLEAR–
  HUNDREDS OR THOUSANDS OF MEGAWATTS?

- FUNDING CRUNCH COMES WHEN DEVELOPMENT OF SPACE BASES AND HLLV'S MUST BEGIN

- SEVERAL COST DEFERRAL OPTIONS–
  BENEFITS OF THESE ARE DUBIOUS UNLESS THERE IS A SIGNIFICANT LIKELIHOOD THAT SPS WILL GO THROUGH BUT NOT BEYOND THE PROTOTYPE (DEVELOPMENT) PHASE